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System Status Display Information

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McDonnell Douglas Corporation
Douglas Aircraft Company
Long Beach, California 90846

Contract NAS1-16202
October 1984

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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665

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SUMMARY

The System Status Display study is part of the Advanced Transport Operating Systems program sponsored by the National Aeronautics and Space Administration's Langley Research Center and is directed toward the development of advanced display information for the flight deck operations of future commercial aircraft. The System Status Display (SSD) is an electronic display system which provides the crew with an enhanced capability for monitoring and managing the aircraft systems (i.e., hydraulics, electrical, etc.). The potential benefits to be gained through the use of electronic displays are improvement in crew performance, reduced probability of error, and more efficient workspace utilization. It is anticipated that these benefits in crew proficiency will significantly enhance the efficiency and safety of terminal area operations.

INTRODUCTION

The overall objective of the current study is to establish general principles and guidelines for the design of electronic system displays. The technical approach to this problem involves the application of system engineering to the design of candidate displays and the evaluation of alternative concepts by part-task simulation. This report covers the system engineering portion of the study and the selection of candidate displays.

The study identifies display information requirements based on detailed analysis of representative flight operations. This analysis includes the development of a sequential iterative model of the crew functions involved in the operation of the aircraft systems. This model is used to develop a task flow diagram identifying all the crew decisions and actions necessary to manage and monitor the aircraft systems. The information requirements for each of these tasks are identified by review of the system operation, mission requirements and flight phase requirements. The information requirements are partitioned into four distinct classes:

IDENTIFIERS. The name or label of an item such as a switch legend.

DESCRIPTORS. Information regarding the elements of a system and their functional and spatial relationships similar to those that might appear in a systems description manual.

SYSTEMS STATUS. The operational state of the system including parameter values such as hydraulic pressure.

INSTRUCTIONS. The operational procedure necessary to establish or modify the system configuration such as the checklist.

This classification scheme aids in the identification of information sources (e.g., system sensors, procedures manual, etc.) and the selection of specific display formats based on knowledge of human information processing and human engineering design criteria.

The selection of alternative display configurations is based upon existing knowledge of human memory coding strategies and memory structure. The basic principle is that the fewer cognitive processing steps required by the crew, the quicker the response and the less chance for errors. In general, comprehension of information regarding the relationships among the system components and dynamics of system operation is facilitated when the information is presented in a format that is compatible with a pictorial or "iconic" memory code. It may also be hypothesized that information regarding a set of actions that are performed serially (e.g., a well defined procedure) can be comprehended more readily when presented in an ordered text format.

Since the System Status Display must perform both functions, optimization of the individual display format requires a full understanding of crew information requirements and how the information will be used within the context of the intended mission. In order to achieve the desired level of display-operator compatibility, three alternative display formats were mechanized for experimental test: pictorial only, printed word lists, and pictorial information with printed word instructions.

The proposed system consists of a display generator, a matrix display, and control and sensor interfaces. The flight hardware would be redundant and would be interfaced with other display components, i.e., the primary flight and the flight management displays. For the simulation, a high resolution three-color shadow mask CRT was used as the matrix display.

In general a display by exception philosophy is used. According to this philosophy, information is presented only if it is required in order for the crew to perform the required task or to inform the crew that the system status or the operational envelope of the aircraft has changed. The crew has the option of calling up more detailed status information at any time.

A summary page is presented as the baseline format for all flight phases unless the crew calls up a systems page. The summary page contains alphanumeric alerts and selected system parameters that are relevant to the particular phase of flight. A dedicated control panel may be used to call up a systems page. The first systems page presents the status of the system. Additional pages contain more detailed information and may be called up by the advance page key. The first line of the systems page (see Figure 9 for example) contains identification of the system and alerts if any exist. The next three lines are reserved for procedures. The remainder of the display contains the pictograph or the printed word formats. Established display design guidelines based on human engineering and graphic design principles were used to generate the display formats. Alternative display formats were generated for the fuel, hydraulics, and the flight control systems.

BACKGROUND

Advances in digital electronics and CRT technology add new dimensions to cockpit designs. These advances allow increased versatility in the crew interface design and the assignment of crew roles in flight and system management functions. The major portion of the crew tasks in aircraft systems management involve monitoring system status and detecting system faults. Our present knowledge of human capabilities and limitations indicates that routine monitoring functions can be performed more efficiently and reliably by automatic devices. The inherent capability of contemporary electronic equipment will allow the designer to allocate many of these functions to automated elements of the system. The crew will then be able to devote more attention to primary duties of decision making and flight management.

Increased automation offers the potential for reducing the crew workload. This is counteracted to some degree by a trend toward increasing system complexity, a reduction in crew size, and constraints on workspace layout. These factors tend to modify traditional crew roles and duties. The proportion of time devoted to systems management tasks has increased substantially while manual control task demands have decreased. Instead of manually operating the aircraft, the crew performs primarily analytical functions. This change in crew roles has raised some flight safety issues. In a review article on the role of the crew and automation in flight, Weiner and Curry (1980) identified several issues that have a potential impact on flight safety. The primary concerns expressed by Weiner and Curry were the failure of the crew to recognize and respond to failures of automatic equipment, and the loss, or lack, of learned skills to perform in a manual backup mode.

Over the last six years, Rouse (1981) has investigated the role of automation in aircraft applications. As a result of his research studies and the recognition of the safety issues, he proposes the following:

1. An adaptive automation wherein under normal conditions, the crew performs manual operations and, as the workload increases, automation is used to assist the crew. This allows the crew to maintain their skill level and have the advantages of automation when it is necessary.
2. As an aid to problem solving tasks, the computer is used to prompt the crew, i.e., the computer assists the crew by tracking crew actions and telling the crew the implications of their actions. Rouse's empirical studies have found that this type of assistance reduces the number of human errors.

The traditional duties of the crew in the management of aircraft systems include operational switching of system hardware, on-line monitoring of system status for faults or changes in the system, and reconfiguration of the aircraft system when a fault is recognized. Current commercial aircraft have substantial automation and redundancy at the system level as opposed to the display level. The crew interface is composed of hardwired, dedicated electromechanical displays and controls. Fault detection logic and annunciation are built into most aircraft systems. These fault annunciations are simple out-of-tolerance detectors and are hardwired to an annunciator light, an aural alarm, or a voice warning device. Current aircraft have a large number of annunciators and the simple logic contributes to a large number of false alarms. These false alarms have been a major concern of pilots and system designers (Cooper, 1977 and Randle et al., 1980). Recently, the Federal Aviation Administration has been supporting an effort to arrive at design standards for a commercial transport aircraft's cockpit alerting and warning system (Boucek et al., 1981). These standards include priority and inhibit logic for presenting warning, cautionary, and advisory alerts.

The concept of a computer aided, multifunction system management display first appeared in the early 1970's. Bauerschmidt and La Porte (1976) suggested that it was the advent of CRT displays and digital processors that allowed the concept of a multifunction display to become a reality for status monitoring. They reported that such a display has many potential advantages including improved reaction time, decreased error rate, and a simplified hardware interface.

The use of a CRT system monitoring display and a digital computer was incorporated into a study performed by Hughes Aircraft Company for the Air Force (Streeter et al., 1973). This display presented functional status values, caution and warning annunciations, mode advisories, and checklists. The hardware consisted of a single CRT with multifunction switches whose functions were indexed by legends on the CRT display, and a digital display processor. The page formats of the CRT were printed word lists and the structure of the page varied according to the nature of the fault. Evaluation of the concept was not reported.

Boeing Aircraft Company performed a study for the Air Force with the objective of identifying requirements for multifunction displays in military cockpits (Graham and Broomhead, 1975). This study identified the following requirements but did not provide any supporting data for the requirements:

1. Graphic displays have limited utility and are not required in a multifunction display.
2. When graphic interaction is required, a cursor control is more effective than a light pen or a touch panel.
3. Multifunction switches should be programmed by peripheral equipment and be capable of changing modes automatically.
4. Functional data or parameter values should be displayed.
5. A system should be designed to provide maximum utility and minimum workload.

In a study conducted by the Air Force (Bateman et al., 1980) multilegend switches, CRT indexed switches, and CRT page formats tailored to a specific fault versus a branching logic were evaluated empirically. The first page of the format with the branching logic provided a summary of the system and subsequent pages provided more detailed status. The results of this evaluation showed that response times and errors were less for the multilegend switches and the tailored logic was superior to the branching logic.

McGee and Harper (1980) described a status monitoring system for a rotary wing aircraft. This concept used a single CRT display to present status, procedures, and parameter values. Dedicated switches were used for CRT page call up and systems control. The CRT formats were printed word lists for status and procedures, and bargraphs for parameter values. The design concept was not evaluated.

A forerunner of the current project at Douglas Aircraft was an engine monitoring and display system, EMADS (Mas et al., 1979)., EMADS is an integrated engine management system composed of a CRT display, a dedicated control panel, and a display processor. The display formats contain structured tables of status information and bargraphs of engine parameters. The display provides engine alerts and procedures for correcting the alerts, thrust commands and limits, trend information, and checklists for prestart procedures and flight planning. The EMADS display system was recently evaluated against conventional instrumentation in performance of normal and emergency operations (Po-Chedley, 1981). The results of this evaluation showed that pilot performance with EMADS was better or the same as that obtained with conventional instruments. Subjective evaluations by operational pilots were favorable towards EMADS.

Current operational aircraft with multifunction system monitoring displays include the McDonnell Douglas F-18 and the Airbus Industries A310. The F-18 has a monochromatic CRT display and uses indexing keys for menu and mode selection. Index keys are located on the CRT's edge with the key's legend on the CRT. System status switching is performed by dedicated switches and the CRT page formats are printed word lists of status, procedures, and parameter values. Limited graphics are available. The A310 is the first airliner to incorporate a multifunction status monitor. This unit is called the Electronic Centralized Aircraft Monitor (ECAM) and it is redundant to the dedicated instruments contained in the center and overhead panel. The ECAM consists of two high resolution color CRT displays located in the center instrument panel and a dedicated switch panel located on the pedestal. Dedicated system switches are located in the overhead panel. The left CRT pages contain printed word fault annunciations, status lists, and procedures. The right CRT contains schematics, graphics and/or numeric displays of parameter values.

It is apparent that there are advantages to multifunction system status displays and they will be incorporated into future aircraft. The primary advantages of computer driven displays are to aid the crew in the detection and recognition tasks, to provide prompting, decision aids, and flexible display formats. Although previous studies provide some design guidance, there are a number of design alternatives and issues that need to be addressed. Key questions to be answered may be summarized as follows:

1. What is the role of the crew in reconfiguring redundant systems? Should his role only be as a passive monitor of an automated system or should he participate actively in reconfiguring the system?
2. Depending on his role, what information should be presented to the crew? What system engineering methodology should be applied for specifying the information requirements?
3. What format should be used for displaying the information to the crew?
4. What control interface devices should be used? Should dedicated controls be used or is it possible to integrate the control interface with the displayed information?

The approach used in answering these questions included the development of a candidate system concept, the utilization of system analysis techniques to identify the information requirements, and the selection of candidate display/control formats and hardware based upon the technology that will be available for the next generation aircraft. The intent is to evaluate the alternative configurations using part-task simulation.

DEFINITION OF THE SYSTEM STATUS DISPLAY CHARACTERISTICS

The first step towards the development of a candidate concept was to review the various approaches to aircraft systems management and to identify the basic hardware configuration for the SSD. This was accomplished by surveying system designers and flight operations personnel regarding system management and display/control philosophy.

INDUSTRY SURVEY

Initially, an in-house committee composed of flight operations personnel, design engineers, and human factors engineers held a series of meetings to discuss the issues involved and arrive at a preliminary system concept. Subsequently, a detailed questionnaire was distributed to system design engineers and flight operations personnel to solicit their opinions on the design issues. The results of this questionnaire are summarized in Appendix A. This questionnaire was revised and it formed the basis for a structured interview with the research and development personnel from three other airframe manufacturers: McDonnell Aircraft, St. Louis; Lockheed, Georgia; and Boeing, Seattle. These interviews solicited opinions on the design issues and approaches to system management displays. The questionnaire and the responses to the interview are contained in Appendix B.

SYSTEM DESCRIPTION

As a result of these surveys, the following system concept was formulated:

The SSD serves as a crew interface for all systems except the flight guidance, flight management, and the radio management systems. The latter systems have separate crew interfaces. The SSD consists of dually redundant computers and CRT displays (or flat panel matrix displays). The SSD computer receives data from and sends data to the peripheral aircraft systems, the flight guidance computer, the flight management computer, and the caution and warning system. The SSD computer drives the CRT displays and receives crew inputs via multifunction switches. A conceptual block diagram of the system is shown in Figure 1. In addition, there are dedicated, hardwired displays and controls for backup or when electrical power is not available.

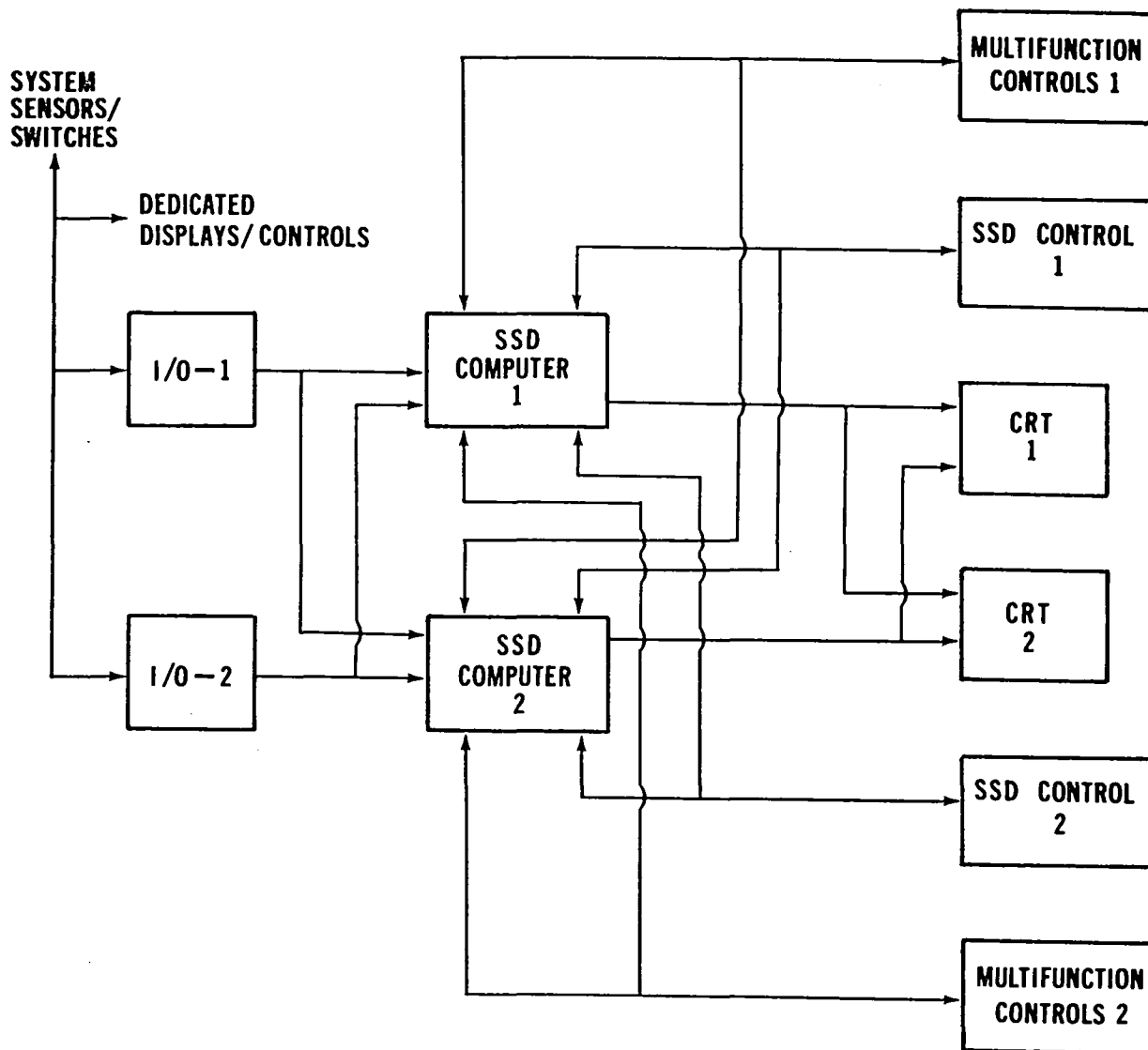


FIGURE 1. CONCEPTUAL SYSTEMS ARCHITECTURE FOR THE SYSTEMS STATUS DISPLAY

The general display design philosophy is display by exception. That is, the mode of operation for both normal and abnormal conditions is to present only the information necessary to inform the crew of changes in the operational envelope of the aircraft and to reconfigure the system. However, detailed status information is made available to the crew upon demand.

The following features and capabilities are prime candidates for incorporation into the SSD.

DISPLAY FLEXIBILITY. Computer generated displays allow flexibility in the display content and format. The display formats are standardized and are designed to improve the crew's ability to interpret and use the information. It is anticipated that this flexibility will increase the efficiency of crew operations, i.e., reduce the response time and reduce the number of crew errors.

INFORMATION STORAGE AND PRESENTATION. Crew procedures and system descriptions are stored in the computer and displayed in formats that are compatible with the presentation of status information. The computer is used to monitor the crew actions and prompt the crew for the next action or alert the crew if an incorrect action is performed. The system provides feedback to the crew regarding the results of their actions and annunciates changes in aircraft status or operating restrictions.

FAULT DETECTION AND PRIORITIZATION. Fault monitoring and detection occur within the peripheral systems. Prioritization of faults and flight phase inhibit logic occur within the SSD computer or a separate caution and warning system. The fault system uses the guidelines set forth by the FAA Aircraft Alerting Systems standardization study (Boucek, et al., 1981). Higher order monitoring, i.e., interpretation of fault conditions when multiple failures occur and the analysis of trends are considered desirable characteristics to be incorporated into the fault monitoring logic.

ALLOCATION OF FUNCTIONS BETWEEN THE CREW AND AUTOMATED EQUIPMENT. The level of automation of the system is the responsibility of the individual system designer. As a rule, the system should operate in a hands off mode (i.e., it should be designed with a minimum amount of monitoring and control required). System redundancy should provide a fail operational capability (i.e., there should be automatic switching between redundant systems). In general, the crew should only become involved in a systems operation if the operational capability of the aircraft or the mission is affected.

INFORMATION REQUIREMENT ANALYSIS

Within the conceptual framework defined above, the definition of the display content was based on a thorough analysis of crew information requirements. This approach consisted of a task analysis, identification of required information, an operational sequence analysis, and classification of the information. The study was initiated by reviewing the normal and abnormal procedures for two current commercial aircraft: The MD-80 and the DC-10-30. This review resulted in the decision to perform an in depth analysis of two systems and to develop the guidelines and representative formats for these two systems. The two systems selected were the fuel and the hydraulic systems. The selection of these systems was based upon their relevance to safety during the critical phases of flight (i.e., a hydraulic failure impacts the flight controls and a fuel failure could affect the range, gross weight, and balance of the aircraft).

The candidate designs for the fuel and the hydraulic systems used in this study are likely candidates for a next generation, two engine, two man crew, commercial aircraft. The designs are based upon DC-10 technology with multiple levels of redundancy and include automated features anticipated by system designers. Descriptions and block diagrams of these two systems are presented in Appendix C.

Task flow diagrams were generated for the two systems. A generic example is shown in Figure 2. These diagrams were generated by using a sequential, iterative model to describe the crew-system operations.

According to this model, the process of managing the aircraft systems involves periodic review of system status. Elements of this monitoring function are performed automatically and the outcome of the status check will determine what actions (if any) are taken. The general flow contains three basic steps:

1. Check to determine if the system configuration is nominal and, if not, reconfigure the system.
2. Check to determine if the actual configuration agrees with command configuration.

3. Check the status to determine if the system is operating properly and, if not, a contingency procedure is entered.

The remainder of the task flow is designed to accommodate variations in information requirements as a function of flight phase and to access information required for entering the next flight phase.

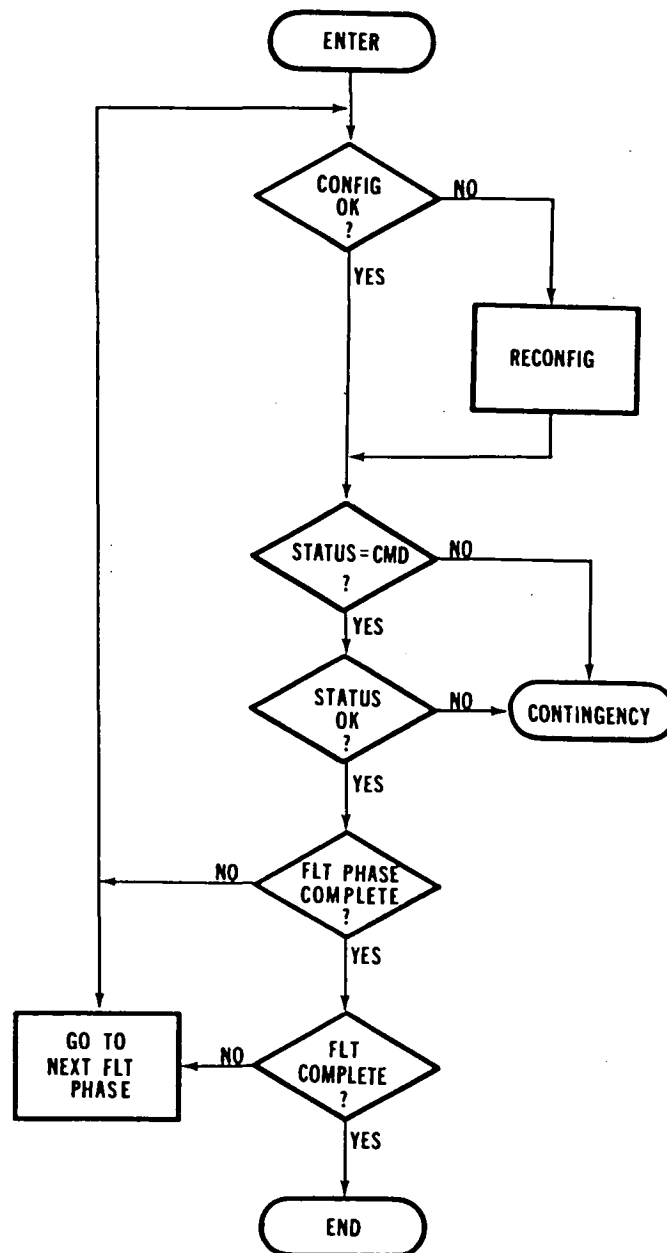


FIGURE 2. GENERIC TASK FLOW DIAGRAM

The task flow shows only the decisions and actions required to complete an operation. The next step in the analysis is to identify the information required to make the decisions and/or to perform the actions. The information requirements were identified by reviewing each element in the flow diagram in terms of specific input parameters required, the pilot's knowledge of the system, and operating procedures for necessary control of the system. Subsequent to the information requirements analysis an operational sequence analysis was generated to identify the sequence of steps for collecting the information and performing the necessary decisions and actions.

For both the fuel and hydraulic systems, two procedures were analyzed: the normal operating procedure and one contingency. The fuel contingency was a tank imbalance advisory and the hydraulic contingency was a dual hydraulic failure resulting in partial failure of the flight controls. These three analyses: the task analysis, the information requirement analysis, and the operational sequence analysis are presented for both systems in Appendix D.

To assist the development of display formats, the information was classified according to the way in which the information is used by the crew. This classification scheme aids in the identification of display alternatives and application of human engineering principles to determine the optimum format. The information requirements were partitioned into the following four basic classes:

1. IDENTIFIERS. The name or label of an item. The source may be either a legend or the crew's memory.
2. DESCRIPTORS. Information regarding the elements of a system and their functional/spatial relationships. The source is either the crew's memory, the systems description manual, or aircraft instrumentation.
3. SYSTEM STATUS. The operational state of a system including any parameter values. The source is the system sensors and aircraft instrumentation.
4. INSTRUCTIONS. The operational procedure necessary to establish or modify the system configuration. The source is the checklist, the crew procedures manual, the crew's memory, or aircraft instrumentation.

DISPLAY ANALYSIS

Options for displaying information in current aircraft are limited to a large extent by the inflexibility of conventional display media. Switches are labeled by printed alphanumerics, parameter values are displayed by electromechanical instruments (i.e. pointer dials, vertical tapes, or numerical readouts) and descriptive and procedural information is presented in manuals using a combination of printed words and pictorial formats. Recently, there has been an attempt to layout the components on the control panels according to their functional/spatial relationships in the aircraft.

The utilization of digital computers for the processing and storage of information increases the flexibility of presenting information to the crew and offers the potential for enhancement of the crew interface. Given the numerous alternatives for display formats, the problem of identifying the format which the crew is able to comprehend and utilize most effectively becomes critically important.

The approach to addressing these issues was to first review the display and control hardware alternatives and to select the most viable alternatives for empirical evaluation. The second step was to review established human engineering and graphic design principles to arrive at a set of guidelines for the SSD display formats and to apply these guidelines in the development of alternative formats for empirical evaluation.

DISPLAY AND CONTROL ALTERNATIVES

The last decade has produced major advances in flight deck technology. One of the most significant ones is the replacement of the electromechanical displays with computer-generated imagery on CRT displays. This has allowed the tailoring of display formats to be compatible with the crew's ability to interpret the information and to use multiple formats on a reduced number of display surfaces. The advances in the control interfaces have been somewhat slower. Current commercial transports use dedicated control panels with few exceptions. However, there are several multifunction control alternatives which could be incorporated within the next decade.

Display Technology

Contemporary electronic display technology employs high brightness, high resolution, three color shadow mask CRT's for primary flight and status displays. These displays have been incorporated into the cockpits of Boeing Aircraft Company's 757 and 767 aircraft and the Airbus Industries A310 aircraft. The attributes of these displays include the following:

1. High brightness which provides readable contrast at ambient illumination levels of 8000 foot candles.
2. High resolution with a minimum resolvable element of .010 to .012 inches.
3. Full color capability using the three primary colors. Although the current units only provide a limited number of fixed colors (i.e., approximately 15) they have the potential for producing a full color spectrum.
4. Versatile image generation using hybrid image generation techniques with both stroke writing and raster fill capabilities.

Flat panel technology has the potential for offering considerable savings in power consumption and space. Although significant developments have been made in liquid crystal matrix displays and thin film electroluminescence panels (Brindle et al., 1980, Knuta, 1981, and Uede, 1981) further advances are required before they achieve the capability and the reliability of the CRT displays. The three-color shadow mask CRT display is considered the most viable alternative for the next decade.

Control Technology

Recently, controls have advanced from toggle and rotary switches to pushbutton switches with backlighted legends. Commercial transport aircraft use dedicated controls (i.e., each control knob or switch has a one and only one function). The only non-dedicated switches have been CRT indexed switches and

keyboard data entry panels on the RNAV and flight management control units. CRT indexed switches are pushbutton switches located on the edge of the CRT with the switch legends located on the CRT. These multifunction switches are used more commonly in advanced military aircraft.

Other approaches include multilegend switches, touch panels, and voice recognition data entry devices. The only commercially available multilegend switches are projection switches using individual incandescent bulbs for each readout. No commercial aircraft use these switches due to their relatively poor legibility at high levels of ambient illumination. Other alternatives are LCD, LED, or thin film electroluminescence alphanumeric matrices on the switch head. Development of these switches require advances in the state of the art but they could be available for the next generation aircraft. Touch sensitive panels are transparent overlays on the CRT display wherein a switch is activated by touching a specified area on the display. Feedback is provided by an audible tone and/or a visual change on the CRT display. Several technologies have been used for touch panels and include pressure sensitive panels, electrostatic panels, and LED-photocell arrays. It should only be a matter of time before one of these alternatives become technically feasible. Voice recognition devices are in early development (Mountford and North, 1980) and still require technological advances before they become operationally feasible.

There have been empirical evaluations of CRT indexed switches and multilegend switches (Bateman et al., 1980). It was found that both response time and error were lower with multilegend switches than the CRT indexed switches. This may be attributed to the legend appearing in a different location than the switch with the CRT index approach. Touch panels have been criticized for their lack of tactile feedback (Graham and Broomhead, 1975). There has not been any empirical evaluation of touch panels without tactile feedback or using other forms of feedback.

IMAGE PRESENTATION CONCEPTS

In reviewing relevant literature, it was found that inadequacies exist in the present guidelines for design of CRT display formats. Pictures, schematics, word messages or some combination of the above have been proposed. Available

data indicate pictures are better than words in communication of information regarding objects and their spatial/functional relationships and tend to facilitate association learning. Words appear clearer in meaning, are considered essential for presentation of abstract concepts, and are regarded by developmental psychologists as important in the formation of logical, sequential operations.

A partial explanation of these differences is supported by research in human memory coding. Pictorial information is believed to be stored in a direct memory code which bears a close relationship to the sensory experience that gave rise to it (Haber, 1970). Words are stored in phoneme (speech utterances) codes or by the visual presentation of the phonemes (written language). To relate the phoneme code to the visual sensory experience requires a transition from the visual image to the spoken language and then to the phoneme code. These operations require additional mental processing steps when compared to direct storage of a visual image.

Two relevant studies have evaluated printed versus pictorial formats. Booher (1975) compared six picture word formats for instructions: print only, pictorial only, and four combinations of print and pictorial. The four combinations included: (1) primarily pictorial information with short verbal statements for the actions required, (2) primarily verbal information with pictures for object identification, (3) primarily pictorial information with redundant words, and (4) primarily verbal information with redundant pictures. The results of this study showed pictorial information is important for speed but word information is necessary for accuracy. Comprehension of instructions was most efficient with a combination consisting of primarily pictorial information with short verbal statements for the actions. In another study by Tullis (1981), four different CRT formats were evaluated: a narrative printed format, a structural tabular format, a black and white schematic, and a color schematic. The results showed that response times were consistently faster for both of the schematic formats while accuracy did not vary between the formats.

The shorter response times support the concept that retention of pictorial information requires fewer mental processing steps than words. Based upon

this theory, pictorial imagery should be used as much as possible. However, this depends upon the type of information to be transmitted. Nominal information, i.e., information known through the senses rather than intuition and thought, should be pictorially displayed since it has a direct visual code. Noumenal information, i.e., information conceived by reason, does not have a visual image and must be coded in a graphic or a verbal language.

It can be hypothesized that identifications, descriptions, and status information are best presented in pictorial imagery or a combination of pictorial and alphanumerics. Instructions which do not have a direct visual imagery could be presented as or more effectively with words. If mental imagery is required for interpretation, instructions will require more processing steps than pictures. However, a highly structured sequence of operations might be performed quite easily with printed instructions.

Human memory studies have demonstrated that abstract and symbolic information is stored in long-term memory by different structures (Posner, 1970). The simplest form of structure is a list. More complex structures exist including matrices where the dimensions of the matrices represent different attributes, e.g., a branching or hierarchical structure. One complex structure is the physical layout of the system in the aircraft. Symbolic diagrams showing the functional relationship of components or schematics is an example of another type of structure. Another structure would be a procedural sequence or a task flow diagram.

Based upon the above review, it appears that the best method of presentation would be a pictorial diagram of the system with printed instructions. In order to evaluate the above concept, it is proposed to test the hypothesis that significant differences in crew performance would be found between the following conditions: pictorial without instructions, pictorial with printed instructions, and alphanumerics consisting of printed word lists and printed instructions. Table 1 shows the three experimental conditions and the comparisons that would be made by the evaluation. The display page formats are described in detail in a latter section of this report.

TABLE 1
ALTERNATIVE DISPLAY CONCEPTS AND COMPARISONS FOR
THE EXPERIMENTAL EVALUATION

ALTERNATIVE FORMAT CONCEPTS

CONCEPT	FUNCTION	
	DESCRIPTION	INSTRUCTION
1	PICTORIAL	NONE
2	PICTORIAL	ALPHANUMERIC
3	ALPHANUMERIC	ALPHANUMERIC

EXPERIMENTAL COMPARISONS

CONCEPT COMPARISONS	INFERENCE
1 AND 2	DO SUPPLEMENTARY WRITTEN INSTRUCTIONS IMPROVE PERFORMANCE WITH A PICTORIAL FORMAT?
1 AND 3	WHAT IS THE RELATIVE EFFECTIVENESS OF PICTORIAL AND ALPHANUMERIC FORMATS?
2 AND 3	CAN DESCRIPTIVE INFORMATION BE PRESENTED MORE EFFECTIVELY WITH A PICTORIAL REPRESENTATION?

DISPLAY FORMAT GUIDELINES

As a result of the above analysis and the utilization of standard principles for human engineering design (Semple et al., 1979 and Krebs et al., 1978) and graphic design (Morse, 1979 and Marcus, 1980), the following guidelines were established for the development of the display formats.

General Guidelines

1. Labels, status, and system descriptions are coded by shape or identified by alphanumerics.
2. Printed action verbs are used for instructions and the object of the action is identified by a symbol or a word.

3. Color is used to indicate the operating status of a system. Five colors are used:

- a. White for the identification and system description.
- b. Green for indicating normal status or normal operation.
- c. Blue for advisory status.
- d. Amber for caution status or to indicate a partial failure.
- e. Red for a warning status or to indicate a total failure.

The brightness contrast of the five colors will be adjusted so that they are nearly equal. The colors will be displayed against a black background.

4. Alphanumerics are of uniform intensity. One size is used for the majority of the information. A larger size is used only to identify the system. The size will be based upon the eye design reference point and will be large enough to provide 100 percent recognition of color symbols. Capital letters will be used and the font style will be sans serif.
5. In general, a display by exception design philosophy will be applied and only information necessary to perform the required action will be displayed. In some cases, this philosophy may be modified in order to avoid unnecessarily frequent or distracting changes to the display formats.
6. The crew will have the option to call up additional, more detailed information. This information will be added to the simpler uncluttered display by using an overlay.
7. Disagreements between the command status and the actual status of a system will be sensed and displayed as a fault.
8. Both graphics and text should be presented as simple as possible without degrading the content. There should be geometric separation of functional groups on a display page with empty spaces in between to increase the legibility of display elements.

Pictorial Format Guidelines

1. Pictographs will be used to represent system components and their functional arrangement. A representative set of pictographs are presented in Figure 3.

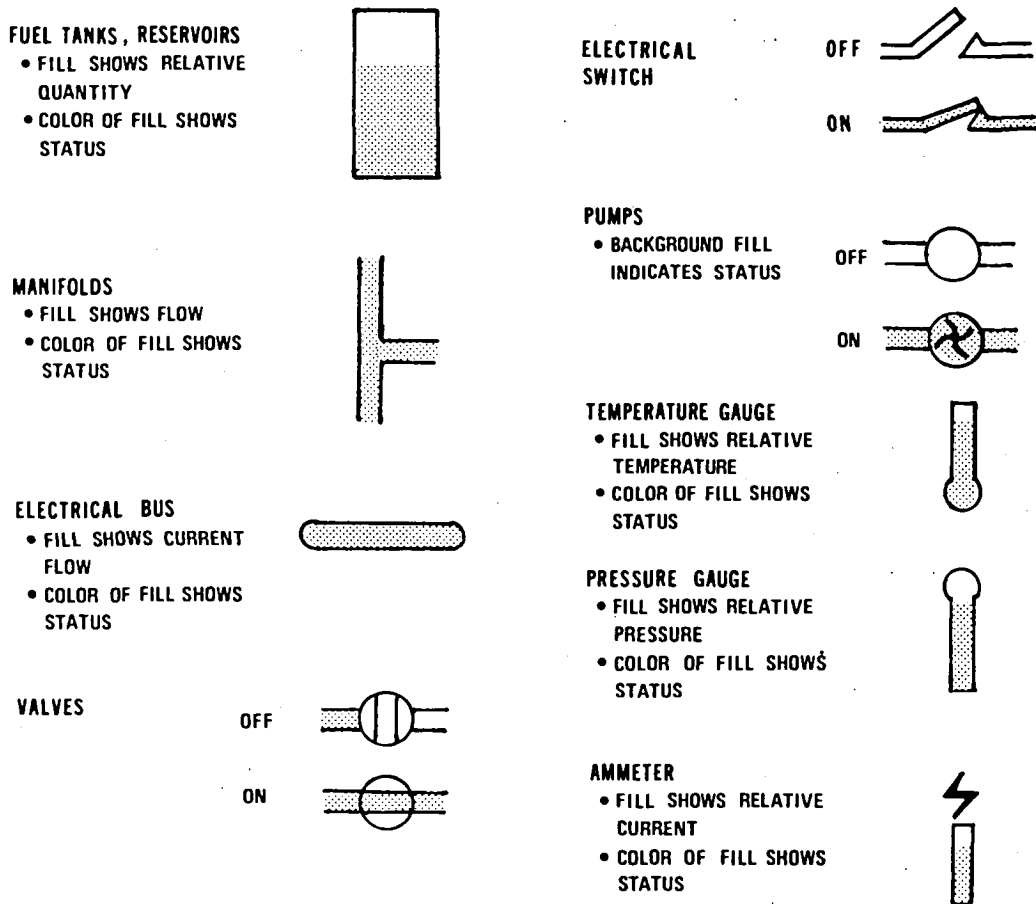


FIGURE 3. PICTOGRAPHIC SYMBOLS USED IN THE PICTORIAL DISPLAY FORMATS

2. Connecting lines in the pictograph represent fuel manifolds, hydraulic manifolds, pneumatic lines, and electrical connections. Solid color fill of these lines indicated the operational state of these lines: empty if the system is off, green if it is operating normally, blue if there is an advisory, amber if there is a failure causing a caution status and red if there is a failure causing a warning status.

3. Pictographs representing reservoirs are color filled. The amount of fill represents the quantity within the reservoir and the color represents the operational state.
4. Pictographs representing parameter values, i.e., temperature gauges, pressure gauges, ammeters, etc., are color filled to facilitate quantitative reading relative to scale values. The color represents the operational state. Accurate quantitative readouts are provided by numerics where required.
5. The structure of the pictorial display is a schematic which represents a combination of the physical location and the functional relationships of the system and their elements within the aircraft. The general hypotheses is that a pictorial schematic presents the least abstract visual image of a system and it should require the least amount of mental processing to store the image or recognize changes in the image.

Printed Word Format Guidelines

1. Noun phrases are used to label or identify a system component.
2. Adjective phrases are used to describe the status of a system component. Numerics are used to provide quantitative parameter values. If interval or ordinal scale information is required, a bar graph is used.
3. As in the schematic system components are grouped according to their physical as well as functional relationships. This word structure provides the only information which relates to system description.

Printed Instructions

1. Action verbs represent a single action or a sequence of activities.
2. The object of the action is designated by an arrow in the pictorial format and by a word descriptor preceding the action verb in the word format.

SYSTEM STATUS DISPLAY EVALUATION

A part-task simulation study should be utilized to further evaluate the alternative display concepts and the control configurations. The part-task simulation would be performed in a fixed base cockpit simulator and would be designed to test the ability of representative sample of pilots to operate the aircraft systems under normal and emergency conditions with primary emphasis on correcting system failures.

The experimental design would be a factorial experiment with the three alternative display formats tested in combination with the three alternative control configurations. Repeated measures would be used on a sample of ten to twelve pilots. A full factorial design would be used to test for interactions between the display and the control alternatives. Training on the respective display/control configuration would be provided prior to initiation of the experimental trials.

Although the system is designed for a normal two-man crew configuration, the experiment will test the ability of one crew member to fly the aircraft and perform the system functions. This will represent a hypothetical worst case condition when a crew member is lost. The test conductor will occupy the right hand seat to provide instructions and observe.

An experimental run would consist of the pilot flying a straight in approach pattern to decision height using the flight director guidance mode. Random disturbances, simulating wind gusts would be used to establish the desired level of workload on the flight task. During the approach, single or multiple faults of the fuel and/or the hydraulic systems would be introduced. The pilot would be required to detect the fault via the master caution and warning system and correct the fault via the SSD while maintaining flight path control. All events would be recorded on a timeline.

The dependent performance measures would be the response time and the response accuracy in correcting the fault. Flight task performance would be measured by the flight path and speed deviations from the desired values. A two-way statistical analysis would be used to determine significant differences between the treatment conditions. The treatment alternatives would be ranked

on the basis of producing the least number of errors while having a minimum effect upon flight task performance. In addition, the pilots would be asked to subjectively rate the different alternatives. The correlation between the subjective rankings and the objective performance measures would be evaluated.

SYSTEM STATUS DISPLAY SIMULATOR

In order to demonstrate and evaluate the alternative configurations a part-task simulator was developed. This simulator uses a fixed base cockpit with computer driven displays and a terrain model system for outside visual reference. The equations of motion, the DC-10 aerodynamics and control system models, and simplified models of two engines, the fuel system, the hydraulic system, and the SSD formats are provided by a Digital Equipment Corporation Virtual Address Extension (VAX 11/780) computer. This is linked to a satellite computer that interfaces the controls, the cockpit and the visual reference terrain model system. The cockpit layout and instrumentation is a modified DC-10. The SSD display is a 6-inch ARINC size C, high brightness CRT located in the lower left corner of the center console that is normally occupied by the standby flight instruments. The remainder of the instrumentation is provided by the DC-10 electromechanical instruments.

The SSD display is driven by a Vector General graphics display generator. This generator is a calligraphic system and allows real-time programming of animated graphics. The format instructions are provided by the host computer.

The SSD has a dedicated control panel in the top left corner of the forward pedestal which is normally occupied by the RNAV control display unit. The SSD control panel uses backlit pushbutton switches and a separate key is used for each system. A system may have more than one page which can be called by advance page or back page keys.

The switches for controlling the fuel and the hydraulic systems are provided in three alternative configurations:

1. A dedicated panel located in the forward pedestal and aft of the SSD control panel. This contains backlighted pushbutton switches. Each system function has a dedicated switch.
2. A multifunction switch panel in place of the dedicated switch panel in the forward pedestal. This panel contains multilegend pushbutton switches using projection switch technology. The function of the switches is controlled by the SSD panel. The switches will display the legends and control the system that is selected upon the SSD panel.
3. A touch panel overlaying the SSD CRT. This panel uses a pressure sensitive membrane. A system function may be changed by touching the symbol or word identifier for the component. An audible tone provides feedback that a switch has been activated and the component's operational state will change on the display.

The location of the SSD display and the control panels are shown in Figure 4. Any differences in performance between the touch panel and the other two configurations could be attributed to the following factors:

1. Separate locations for the system display and the control switch panels versus the same location with the touch panel.
2. Differences in spatial location and reach between the switch panels and the touch panel.
3. Differences in sensory feedback between the switch panels and the touch panel.

Outline drawings of the SSD control panel and the dedicated fuel and hydraulics control panels are shown in Figures 5 and 6, respectively. The multifunction control panel contains a 3 by 5 array of switches. This array has either the legends for the fuel or hydraulic system as shown in Figure 7, depending on which system has been selected.

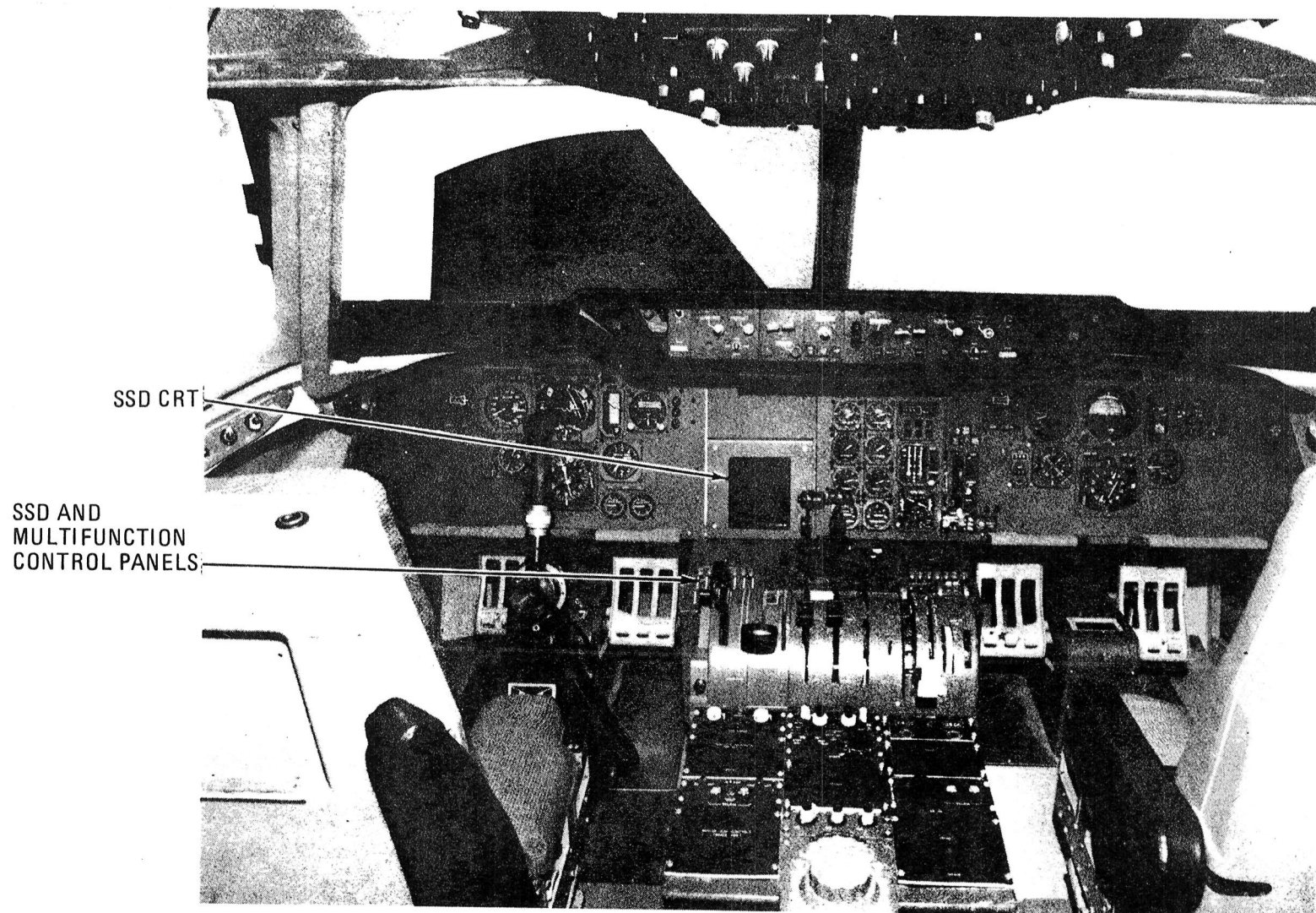


FIGURE 4. FIXED BASE COCKPIT SIMULATOR WITH THE SYSTEMS STATUS DISPLAY

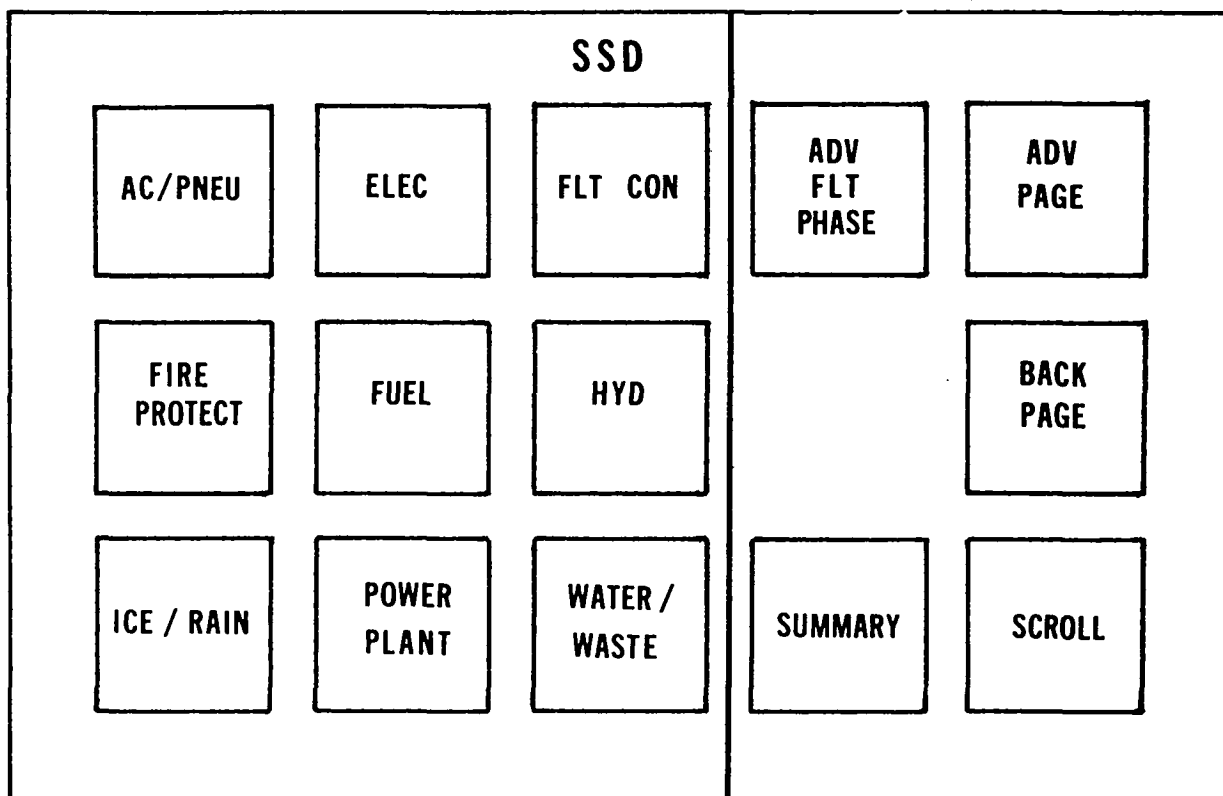


FIGURE 5. SYSTEMS STATUS DISPLAY CONTROL PANEL

CRT FORMATS

The CRT page structure consists of summary pages and system pages. The summary pages contain the alerts and status information pertinent to the phase of flight. The system pages contain fault indications and status information related to a specific system.

Summary Page

The summary page contains a prioritized and sequentially ordered list of alerts requiring the crew's attention. Printed words instead of pictographs were used for this page since the fault list represents a highly structured sequence of recommended actions.

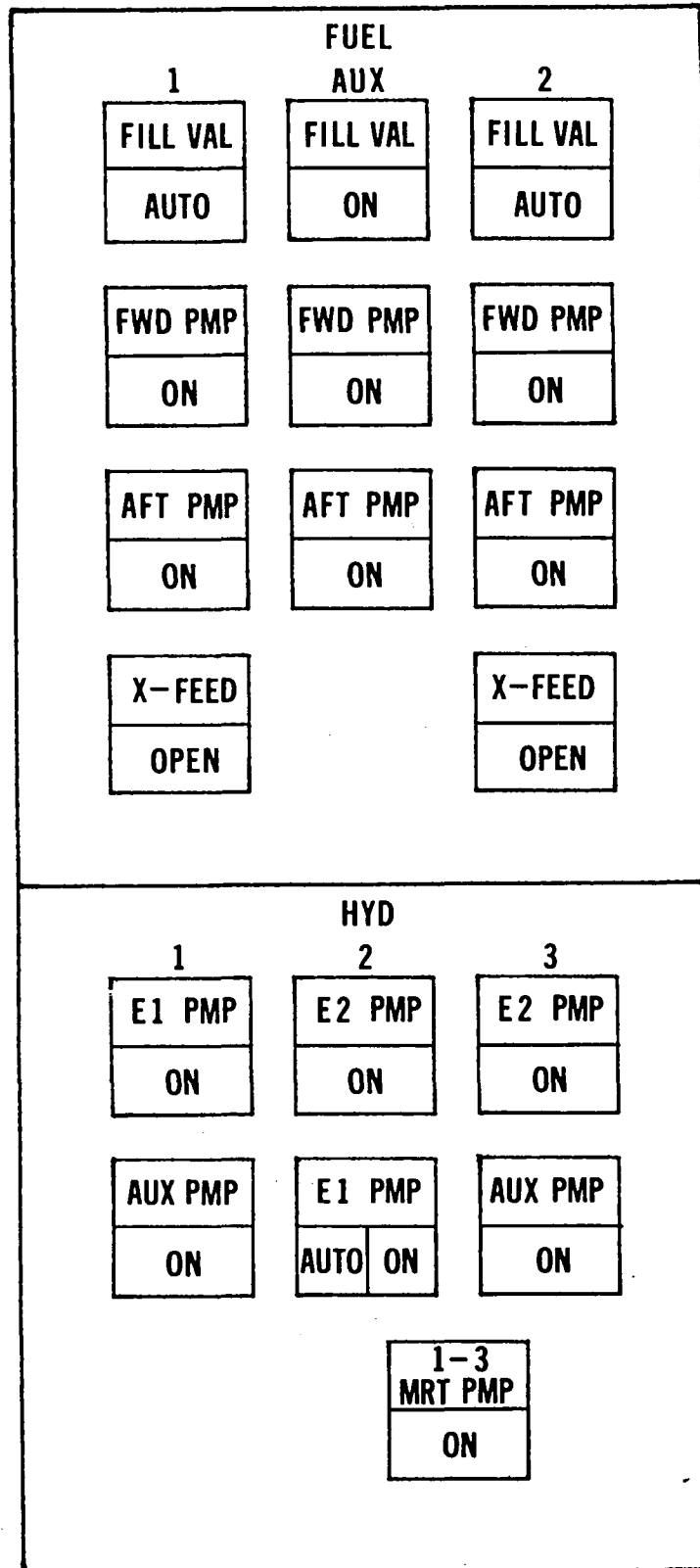
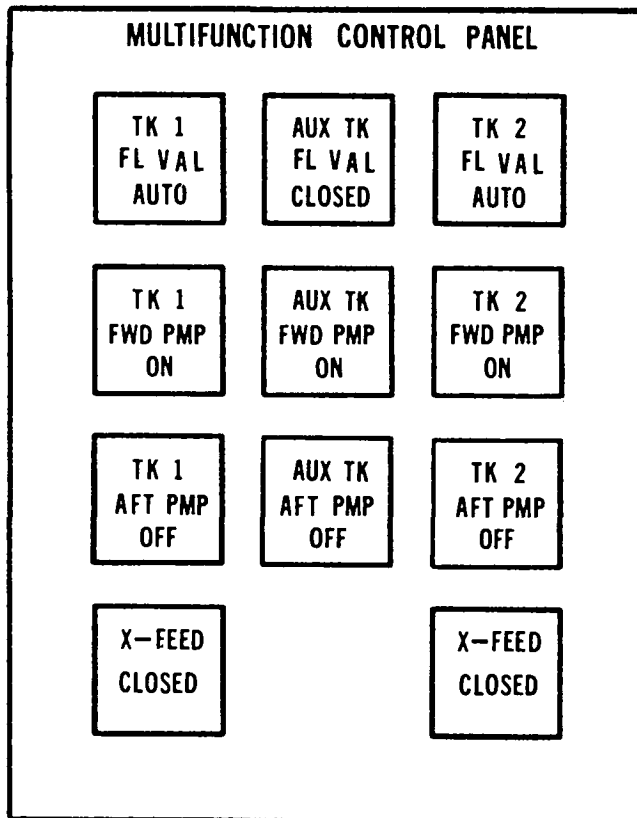


FIGURE 6. DEDICATED CONTROL PANEL FOR THE HYDRAULIC AND FUEL SYSTEMS



**FUEL SYSTEM
CONFIGURATION**

**HYDRAULIC SYSTEM
CONFIGURTION**

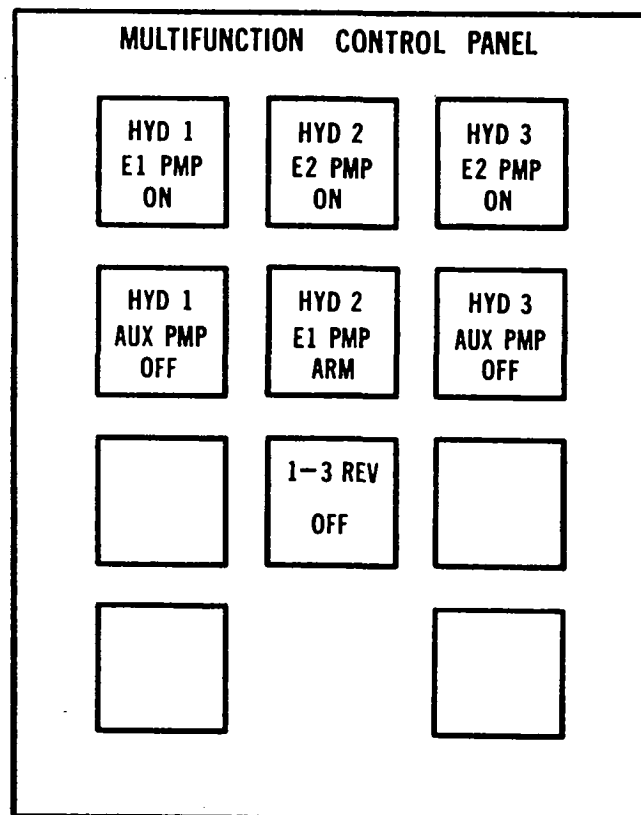
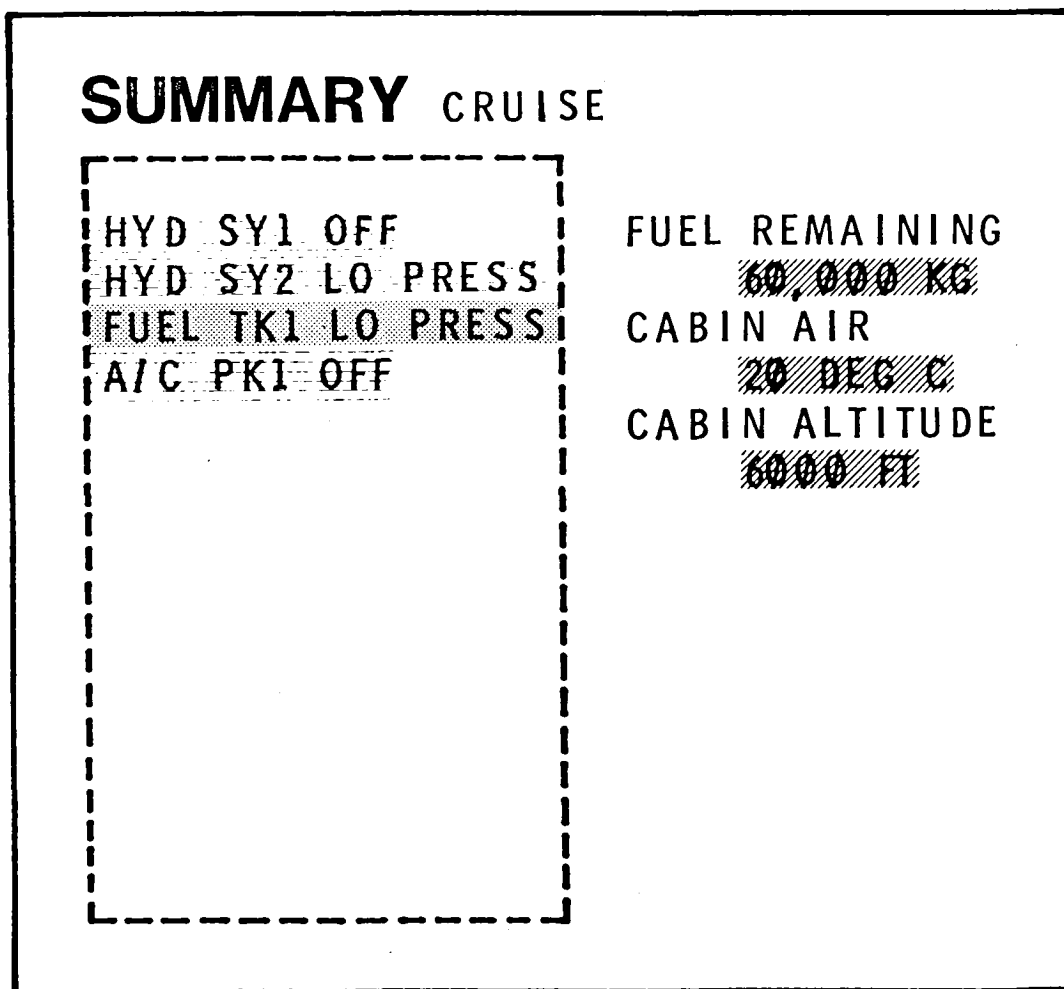


FIGURE 7. ALTERNATE CONFIGURATIONS FOR THE MULTILEGEND CONTROL PANEL

A candidate display page is shown in Figure 8. The first line on the page is used to identify it as the summary page and the page number out of the total number of summary pages is presented in the right-hand corner. The first page of the summary is the nominal display or default condition. However, it may be called up at any time by the summary page key on the SSD control panel. The left-hand portion of the page is dedicated to alerts. There is one alert message per row. The message identifies the system, the component within the system, and the fault. Within a priority category items are listed chronologically with the most recent item at the top of the category.



LEGEND:

RED

YELLOW

GREEN

BLUE

FIGURE 8. FORMAT FOR THE SUMMARY STATUS PAGE

The example shows two font sizes: the larger size is used for page identification and the smaller size is used for the remainder of the information. The larger font subtends a visual angle of 26 minutes with a 4 by 3 aspect ratio and a stroke width of 3.2 minutes. The smaller font subtends a 20 minute visual angle, the same aspect ratio, and a stroke width of 1.6 minutes. This allows 19 rows of fault messages to appear on one page. If there are more than nineteen faults at one time, the lower priority faults appear on a second page.

The right side of the page provides a summary list of checklist procedures to be performed during the flight phase. Once these procedures are completed this information is erased and the remaining information is system parameters which the crew monitors as necessary throughout a flight phase. The example shown in Figure 8 represents the cruise phase of flight.

Systems Page

There is a set of system pages for each aircraft system. These are selected by the system keys on the SSD control panel. The system pages have a summary page and additional pages with more detailed information. There are three alternative formats of each system page for the experimental evaluation.

A typical pictograph page with procedures is presented in Figure 9 and the word list in Figure 10. The first row is used to identify the system and its status. Printed words are used for this identification in order to provide a brief and concise status summary. The first words identify the system, the second words identify the system status which are color coded, and the page number out of the total number of pages is presented in the right-hand corner. The next three rows contain word procedures except for the pictograph-only format (in which case this area remains blank). For the pictorial format with word instructions, an arrow is used to identify the object of an instruction. For the word listing, the object is identified by a printed word prior to the instruction, for example, PUMP 1-OFF. The remainder of the status page contains the pictograph of the system or a structured list.

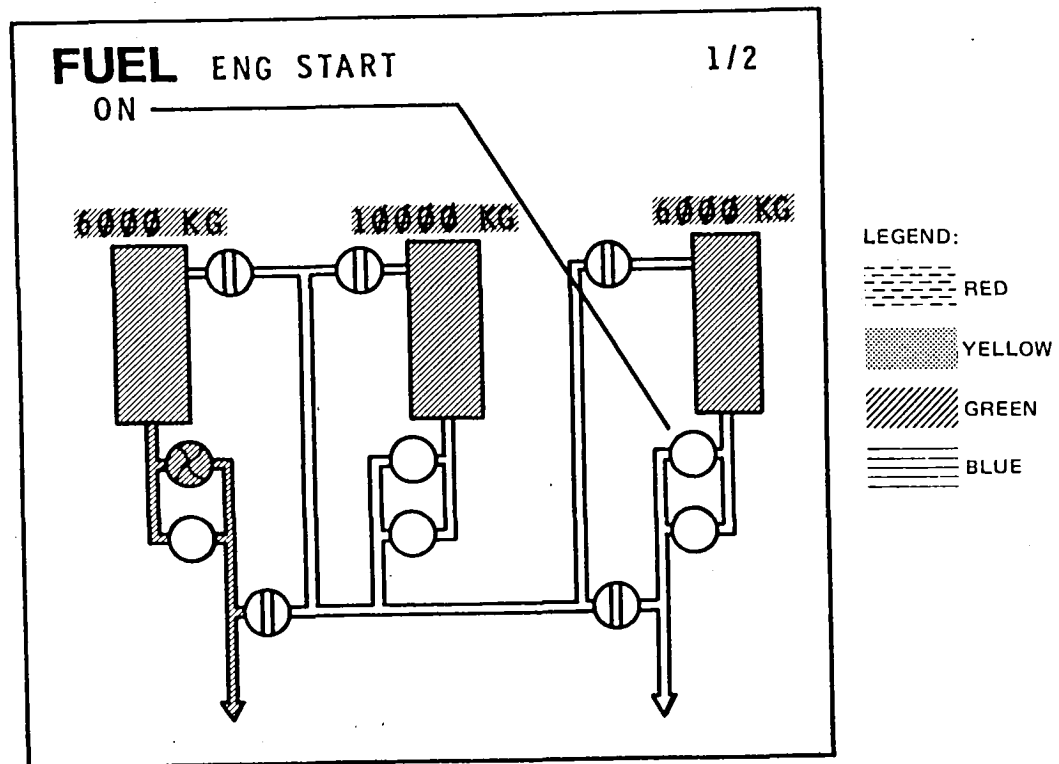


FIGURE 9. PICTORIAL FORMAT FOR THE FUEL SYSTEMS PAGE

FUEL **ENG START** 2/2

TK2 FWD PUMP-ON

TANK 1	AUX TANK	TANK 2
6,000 KG	10,000 KG	6,000 KG
FILL VALVE	FILL VALVE	FILL VALVE
ARMED	CLOSED	ARMED
FWD PUMP	FWD PUMP	FWD PUMP
ON	OFF	OFF
AFT PUMP	AFT PUMP	AFT PUMP
OFF	OFF	OFF
X-FEED VALVE		X-FEED VALVE
CLOSED		CLOSED

LEGEND:

- RED
- YELLOW
- GREEN
- BLUE

FIGURE 10. ALPHANUMERIC FORMAT FOR THE FUEL SYSTEMS PAGE

The information analyses of the fuel and hydraulic systems identified two pages for the fuel system and three pages for the hydraulic system. The first page of each system provides summary information on the status and can be used to reconfigure the system. The second page of each system provides detailed parameter information and it may be called up at the option of the crew. In addition, a flight control surface page may be called up for the hydraulic system since the status of the control surfaces is directly affected by the hydraulic system status.

SYSTEM OPERATION AND PROCEDURES

For normal procedures the SSD provides status information and procedures according to the phase of flight. Each page identifies the systems that require checkout. The crew calls up the system page and proceeds through the checklist presented on the systems page. Upon completion of a system, the crew proceeds to the next system in the sequence until all the procedures are completed. For abnormal procedures, the fault is annunciated by the master caution and warning system and displayed upon the summary status page. The crew selects the systems page to reconfigure the system and determine if there are any changes in the operational limits of the aircraft.

Normal Procedures

When electrical power is turned on, the prestart summary page is displayed upon the SSD. The right-hand portion of the page contains the prestart checks. The crew proceeds to the first system and goes through the procedures. Only three checklist items appear on a page at one time. If the system can acknowledge completion of the procedure, it will automatically scroll the list. Otherwise the crew will be required to depress the scroll key. The crew receives feedback on the completion of a procedure by a change of status on the display. If there is a disparity between the crew action and the system status, a disagree fault is annunciated. The systems page remains on until the crew selects the next page or there is a change in the flight phase (in which case it will default to the summary page). Upon the completion of a checklist, the checklist is erased by depressing the scroll key. The next flight phase summary page may be brought up by selecting the

flight phase advance key or it may occur automatically when certain flight conditions are met (e.g., V speeds, landing gear retract, etc.).

Abnormal Procedures

When a fault occurs, it is annunciated on the master caution and warning system and on the summary status page. The crew member may cancel and reset the master caution and/or warning annunciator at his discretion but the fault will remain on the summary page until it is corrected. Once it is corrected, it is erased from the list. To correct a fault the crew member depresses the system key to bring up the systems page. The systems page identifies the location and the nature of the fault and presents correction procedures. The crew member reconfigures the system using these procedures.

Through activation of a backup component, the fault message is deleted and the failed component is identified on the systems page only. If the system cannot be reconfigured, the fault remains annunciated and the crew reviews the effect it has on the operational state of the aircraft. This is accomplished by depressing the advance key which will show any change in the operational state of the aircraft.

The following example is used to illustrate the operation of the system. Suppose at time T1 an external leak occurs in Hydraulic System 2 which results in loss of pressure. This results in a caution annunciation on the master status page. The first page of the hydraulic system shows loss of fluid in the reservoir and the manifold is filled in amber with the engine pump on (see Figure 11). The procedure is to turn off the engine pump and return to the summary page which now shows system one off. The crew may elect to review the flight control system, but this is optional with the loss of only one hydraulic system. Now, suppose that at time T2, the number two engine pump fails on system two. The system should automatically switch on the number one engine pump but fails to do so. With the loss of pressure in two hydraulic systems, a warning indication occurs and the two failures are shown in red on the summary page. The hydraulic page shows the manifold of systems 1 and 2 in red. The instructions are to turn on the number one engine pump. Figure 12 shows the first hydraulic systems page with the instructions and Figure 13

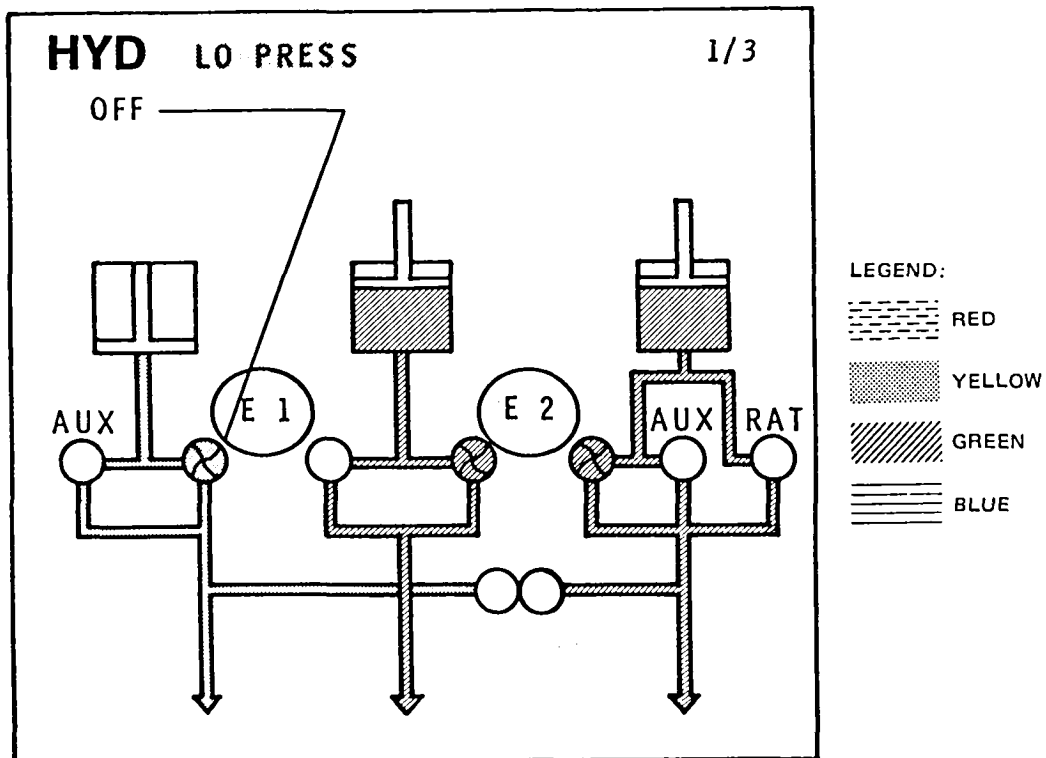


FIGURE 11. HYDRAULIC SYSTEMS PAGE WITH A FAILURE IN SYSTEM 1

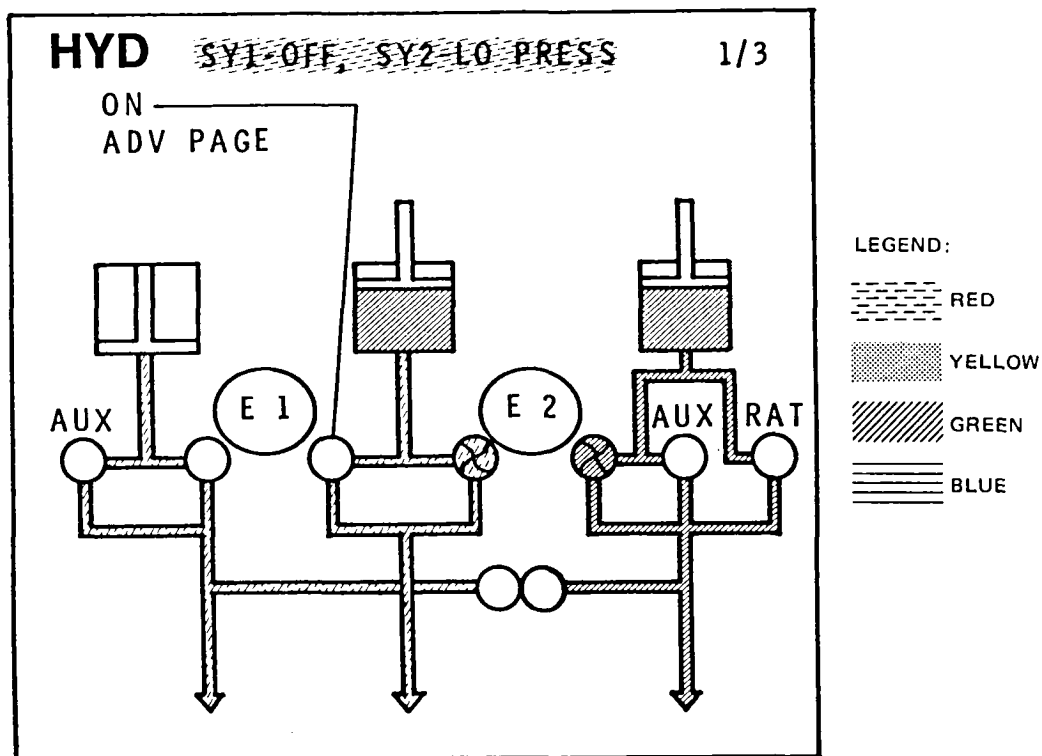


FIGURE 12. HYDRAULIC SYSTEMS PAGE WITH A DUAL HYDRAULIC FAILURE

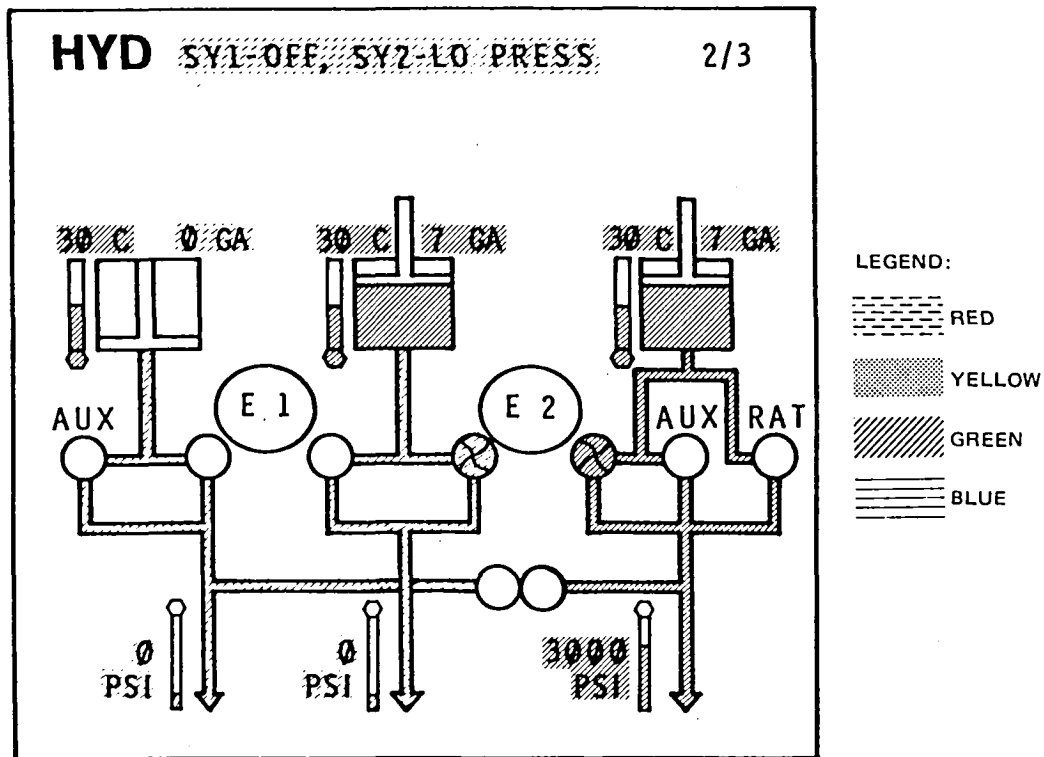


FIGURE 13. SECOND HYDRAULIC SYSTEMS PAGE WITH A DUAL FAILURE SHOWING DETAILED STATUS INFORMATION

shows the second page with the detailed status information that the crew has the option of selecting. If the pump turns on, the manifold turns green indicating normal operation and the alert reverts back to a caution indication.

If the engine pump does not turn on, the crew advances through the pages to or calls up the flight control page. As shown in Figure 14, this page shows the status of the control surfaces in color code where red indicates a failed system, amber a partially failed system, and green a fully operational system. In addition, it shows the actual slat and flap position and indicates the operating speeds for the current configuration. The word list alternative is a listing of the surfaces and their status as shown in Figure 15.

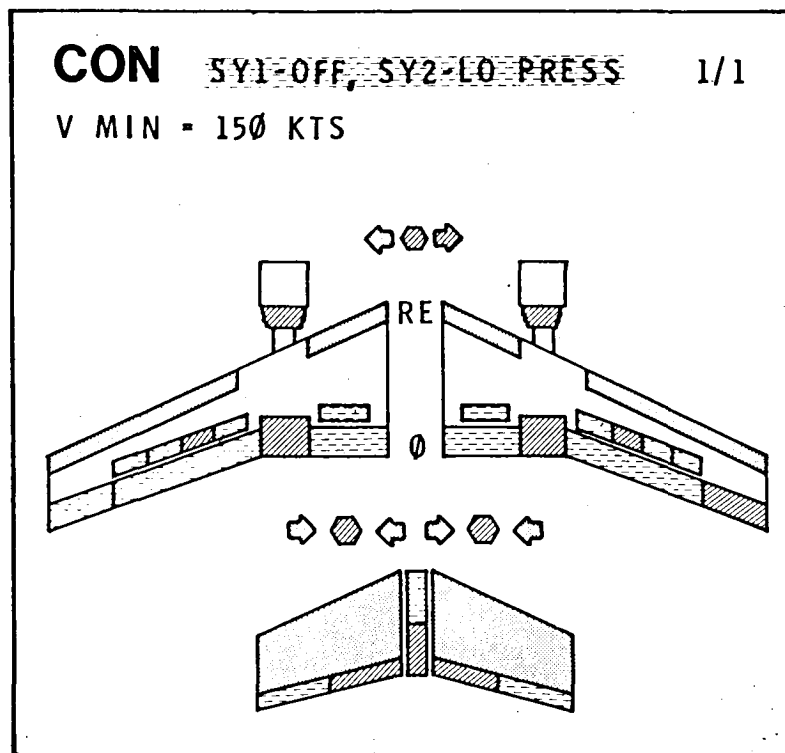


FIGURE 14. PICTORIAL FORMAT FOR THE FLIGHT CONTROL PAGE WITH A DUAL HYDRAULIC FAILURE

CON ~~SY1-OFF, SY2-LO PRESS~~ 1/1
V MIN = 150 KTS

ELEVATORS	L&R OUTBID INOP	
AILERONS	L OUTBID INOP	
RUDDER	UPR INOP	
LG TRIM	RATE REDUCED	
FLAPS	INOP	Ø DEG
SLATS	MAY NOT FULLY EXT	RET
SPOILERS	1, 2, 4, 5 INOP	
BRAKES	SY1 INOP	
REVERSERS	NORMAL	
NSE GR STR	L INOP	
LDG GR	NORMAL	

LEGEND:

- RED
- YELLOW
- GREEN
- BLUE

FIGURE 15. ALPHANUMERIC FORMAT FOR THE FLIGHT CONTROL PAGE WITH DUAL HYDRAULIC FAILURE

DISCUSSION

The results of this study have provided useful insights and guidelines for the design of status displays for aircraft systems. However, there remain a large number of unanswered questions on display formats that will require empirical evaluation and further analysis before a comprehensive set of display guidelines can be presented.

Although it is not a new concept, the systems engineering approach used to identify and classify the information requirements for the various aircraft systems according to flight phase is a viable approach and it is recommended for future design applications. The approach identifies information based upon the crew's need for the information in order to make a decision or perform an action. The analysis classifies the information according to type, (e.g., identifiers, descriptors, parameter values, and instructions). This classification is useful in determining how the information should be presented and the sizing of display pages. Although the information selection was based upon the criticality of the information, no further attempt was made to prioritize it or classify it according to priority. This would require analysis of all the aircraft systems on a timeline and knowledge of their interactions which was beyond the scope of this study.

Another key issue is the role of the crew in systems management and how much automation should be introduced. Analysis did not resolve this question nor will the proposed simulation study provide an answer. To resolve this question requires a larger effort including a comparative analysis of the alternate designs in a longitudinal study (i.e., data collection over a significant period of the operational lifetime of the aircraft) to evaluate the reliabilities of the alternatives. In the interim, there are some rules that can be followed:

1. Automation should be used to achieve an optimum level of crew workload (i.e., to avoid overload or underload).
2. The allocation of functions should provide for an adequate level of operator involvement in order to facilitate reversion to manual modes of operation in the event of an automatic system failure.

3. Information provided to the crew should generally be limited to those parameters that are necessary for performance of required crew duties (with optional crew callup of additional information).
4. For those functions requiring operator awareness or action, the recommendations stated in this report provide a basis for deciding between design alternatives.

The flexibility of computer-generated display formats allow the designer to design display formats that are appropriate for a given level of automation and compatible with crew capabilities and limitations. A number of guidelines for formatting the displays based upon human engineering and graphic design principles have been presented. However, the effectiveness of a particular format depends on the type of operation and conditions of use. Pictorial formats based upon the functional/spatial relationships of a system have an intuitive appeal and there is evidence in the literature to support the concept that fewer mental steps are required to interpret pictorial information. On the other hand, abstraction and higher order thought processes do not necessarily have any relevant pictorial imagery and such information must be presented by some other coding method such as a verbal language. The optimum approach may be a combination of pictorial information for identification, description, and status and alphanumeric information for instructions. A part-task simulation study would be valuable to further evaluate pictorial information versus verbal information and should provide insight into the best format for specific system display applications.

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APPENDIX A

IN-HOUSE SURVEY

Douglas Aircraft design engineers and flight operations personnel were surveyed to obtain their opinions of current system status displays and what they think should be incorporated into the next generation aircraft. Twelve design engineers and six pilots responded to the survey. A summary of the relevant results is presented below.

ADEQUACY OF CURRENT AIRCRAFT STATUS INFORMATION. Except for selected design deficiencies, the majority of the design engineers felt they were adequate as presently implemented. The pilots thought that too much data and extraneous data were presented.

ADEQUACY OF NORMAL AND ABNORMAL PROCEDURES. Some design engineers thought that the procedures were time consuming and did not think they were always followed. The majority of the design engineers thought they were adequate. The pilots stated that too much time was spent on troubleshooting. They suggested simplicity and redundancy are required in order to improve crew operations.

IMPROVEMENTS THAT COULD BE MADE IN NEXT GENERATION AIRCRAFT. Design engineers stated that automatic fault monitoring and reconfiguration should be incorporated. The majority felt that fail-safe operations should be part of the basic systems design and failures should be annunciated with minimum false alarms. Pilots agree with automated switching of redundant systems and fail-safe operation and to display only the limitations that are imposed on the operation of the aircraft.

RATING OF THE DIFFERENT FEATURES OF A MANAGEMENT SYSTEM. The respondents were asked to rate different features of a system management system on their desirability and their feasibility. The consensus of each group is presented in Table A1. The results are presented as a positive (+), an indifferent (0) or a negative (-) attitude towards a feature.

TABLE A1
ATTITUDE OF RESPONDING PERSONNEL TO FEATURES OF A MANAGEMENT SYSTEM

FEATURE	DESIRABILITY		FEASIBILITY	
	ENG	FLT OPS	ENG	FLT OPS
PROCEDURES	+	+	+	0
PROMPTING	+	+	0	—
AUTOCONFIGURATION	0	+	+	—
ALERTS	+	+	+	0
TREND ANALYSIS	+	+	+	0
FAULT DIAGNOSIS	—	0	+	0

APPENDIX B

AIRCRAFT MANUFACTURERS SURVEY

Representatives of three airframe manufacturers were interviewed. These interviews were conducted in order to take advantage of previous experience in the development of system management displays, and from the advanced concepts being developed for NASA Langley. Three companies were interviewed: McDonnell Aircraft, St. Louis, who has developed the F-18 aircraft, Lockheed Aircraft, Georgia, who is developing the advanced crew station for NASA Langley, and Boeing Aircraft, Seattle, who is developing the Functional Requirements for a Multifunction Flight Management Control/display Unit.

McDonnell Aircraft used an iterative design and development cycle for the F-18 cockpit. The requirements, displays, and display formats were developed by a steering committee. The prototype designs were evaluated by simulation wherein both objective and subjective measures were used. The design process was reiterated depending on the results of the simulation. The aircraft uses multifunction displays and status information is provided by printed word lists. Control of the displays is by multifunction switches which are located on the perimeter of the CRT's and indexed by the CRT's.

Lockheed Aircraft is developing an advanced cockpit by a research team composed of system designers, pilots, and human factor engineers. Basically the same approach is being used at McDonnell's, the group develops the concepts and it is evaluated and refined by simulation. The station is a two-man desk top console with six split image CRT displays and side stick controllers. A combination of pictorial and printed word formats will be used. Other data entry devices will be via keyboards and touch panels.

Boeing Aircraft is developing an advanced flight management control display unit. Their approach is to review existing units, review the operational and information requirements, and develop a design concept using hardware components that are available for the next generation aircraft. The basic design consists of a flat panel alphanumeric display and a multilegend keyboard. Page selection is via branching logic.

The survey questions and the responses are presented in Table B1

**TABLE B1
RESULTS OF THE AIRCRAFT MANUFACTURERS' SURVEY**

QUESTION	MCDONNELL AIRCRAFT	LOCKHEED AIRCRAFT	BOEING AIRCRAFT
1) Current cockpit design philosophy is leaning towards the quiet cockpit concept or display by exception. This would mean that the system status information would be displayed when a fault occurs or if the crew is required to reconfigure the system during any portion of the mission. Do you agree with this philosophy? Justify your response.	Display by exception was the basic design philosophy used for the F-18 design. One problem with it is the requirement to present trend information. We had to provide the pilot with predictive cues in the flight director display.	Display by exception is the basic philosophy. Contingencies come up automatically. However, the crew has the ability to erase and recall.	Display by exception is the basic philosophy. However, the crew will still want status information according to flight phase and workload conditions.
2) The display by exception philosophy requires the aircraft designer to be able to identify all probable contingencies prior to their occurrence. Do you believe this is possible? Justify your response.	We used an interactive approach using simulation and flight test to identify those requirements which were not predicted.	Over time an iterative approach will identify all contingencies.	The identification of all contingencies is prohibitive. The designer needs to identify the major ones which are known to be critical to the operation of the aircraft.
3) An alternative to the display by exception concept is to provide comprehensive information to the crew. Is this a viable alternative?	Alternative display formats are displayed upon demand. Both formats are incorporated into the design.	The crew needs the ability to call up a system upon demand. The system will alert the crew to a redundant failure (fail safe) and the crew will have the option to inhibit the alert or call up a detailed display.	Different levels of detail should be provided upon crew demand in addition to the display by exception.
4) Advanced aircraft designs are using multifunction crt displays for system status information. Do you believe all status information should be presented on multifunction displays, or should dedicated displays be used for all or part of the information? Justify your response.	Displays requiring near or continuous lookup should be dedicated. In the F-18 these were the engine and inertial navigation displays.	Dedicated displays are required for emergency power conditions. These include engine, APU, pressurization, ice/rain protection, and exterior lights.	Except for APU start and with proper redundancy, dedicated displays are not necessary. Time or flight critical conditions would be candidates for dedicated displays.
5) One advantage of current avionics technology is the proliferation of digital computers. Computers can aid the crew in performing a variety of tasks. Evaluate the desirability and the feasibility of the following computational aids for both normal and abnormal procedures.			
Information Storage. Menus, checklists, and performance data may be stored, updated, and displayed by flight phase or upon demand.	Yes, checklists should be provided.	Yes, checklists should be provided.	Checklists are desirable. There are developmental problems to overcome.

TABLE B1
RESULTS OF THE AIRCRAFT MANUFACTURERS' SURVEY (Continued)

QUESTION	MCDONNELL AIRCRAFT	LOCKHEED AIRCRAFT	BOEING AIRCRAFT
Prompting. Switch position and operational status of the system may be sensed and, with the aid of computer logic, prompting cues may be displayed to assist the crew.	It would be desirable for critical systems but difficult to implement.	No response.	If the display system is designed correctly prompting is not necessary. It defeats the concept of a quiet cockpit.
Prioritization and Inhibition of Faults. Logic trees may be used to prioritize faults according to criticality or inhibit the fault according to the flight phase.	A combination of sense modalities were used. Voice alerts were limited to the six most critical warnings. Aural alerts were used for nine to ten warnings. The master caution and warning annunciator and visual annunciations were used for all alerts.	The FAA Alert Standardization Study guidelines are being incorporated into the design.	The results of the FAA's Alert Standardization Study are being applied.
Trend Analysis. The rate of change of critical parameter values may be sensed and if they exceed threshold the change in the parameter value is annunciated to the crew.	We were backed into trend analysis and it was not by design. Parameters were arrived at by the steering committee. Thresholds and parameter values were selected by simulation evaluation.	Basically we agree with trend analysis but do not understand how to implement it.	It depends on the role of the crew. If his role is a controller, trend information adds a complication that is unnecessary. If he is a flight manager, you want to provide him with trend information.
Autoswitching. The logic not only detects a failure but it checks the overall status of a system and reconfigures it.	The F-18 cockpit was automated as much as possible and status information is presented to the pilot only if it is flight critical. For the fail safe systems, the crew is notified only if there is a change in the operational envelope.	A fail operational system would not require the crew to interact. However, the crew should be informed of the failure.	The design should allow manual override.
Fault Diagnosis. The logic performs test routines to detect and annunciate equipment malfunctions.	Diagnostics should only be provided if it has an effect upon the mission performance.	Messages should only be presented if the operational limits of the aircraft are affected.	Diagnostics should not be included.

APPENDIX C

SYSTEM DESCRIPTION OF FUEL AND HYDRAULICS SYSTEM

The fuel and hydraulic systems are representative of an advanced two engine two-man crew commercial air carrier. The systems described utilize current technology. Extensive automation was not incorporated in order to have examples with a large number of crew interactions.

FUEL SYSTEM

The fuel supply consists of two main tanks, an auxiliary tank, and two pumps in each tank. A fuel manifold, crossfeed valves, fill valves, and associated controls permit total crossfeed and transfer capability. Fuel from the auxiliary tank is transferred normally to the main tanks through the fuel manifold and the respective tank fill valves. The main tanks have float sensors that turn the fill valve on and off automatically if the auxiliary tank pumps are on and the fill valve is armed. Each pump has a pressure sensor that turns on an annunciator when the pump pressure exceeds 5 psi. If a fill valve sticks in the open position, resulting in an overfill of the main tank, the overfill is annunciated. If there is a fuel imbalance (i.e., there is an imbalance of more than 900 kg between the main tanks) it is annunciated. Pump control and the crossfeed valves are operated manually. A schematic of the fuel system is presented in Figure C1.

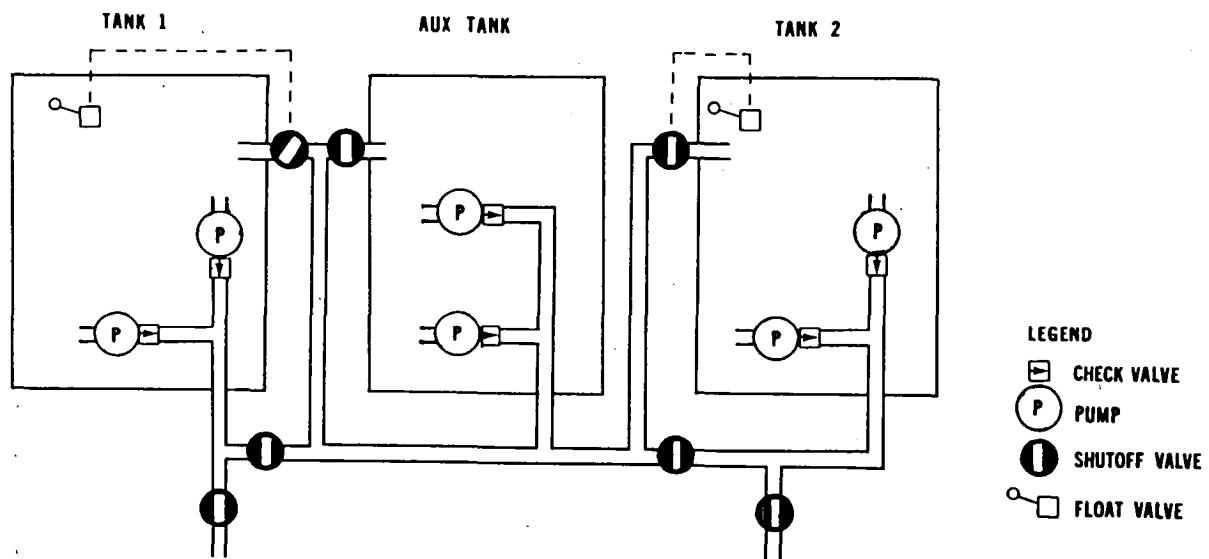


FIGURE C1. FUEL SYSTEM BLOCK DIAGRAM

HYDRAULIC SYSTEM

The hydraulic system consists of three parallel, continuously pressurized systems. System one is powered by a left engine driven pump and an auxiliary electrical pump. System two is normally powered by a right engine driven pump. With loss of pressure in the system, the left engine pump is automatically turned on. System three is powered by a right engine pump, an electrical auxiliary pump, and a ram air turbine. The ram air turbine is automatically deployed during flight if there is loss of hydraulic pressure in system three. In addition, a reversible motor pump will transfer power between systems one and three if more than a 400 psi differential in pressure exists between the two systems. If there is a loss of quantity in either reservoir of systems one and three, the motor pump will shut down. The electrical pumps are used for ground operations but may also be used for emergency operations in case the other power sources fail. A schematic of the hydraulic system is shown in Figure C2.

All three hydraulic systems are isolated from each other so that the loss of one system will not effect the operation of the other systems. Attachment of the hydraulic sensors to the control surfaces are the same as the DC-10 aircraft with the exception of the following: the engine thrust reversers are hydraulically driven and both the upper and lower portions of the rudder have dually redundant actuators. The connections are designed so that the aircraft remains fully operational with the loss of one hydraulic system and the primary flight surfaces remain operable if only one hydraulic system is functioning.

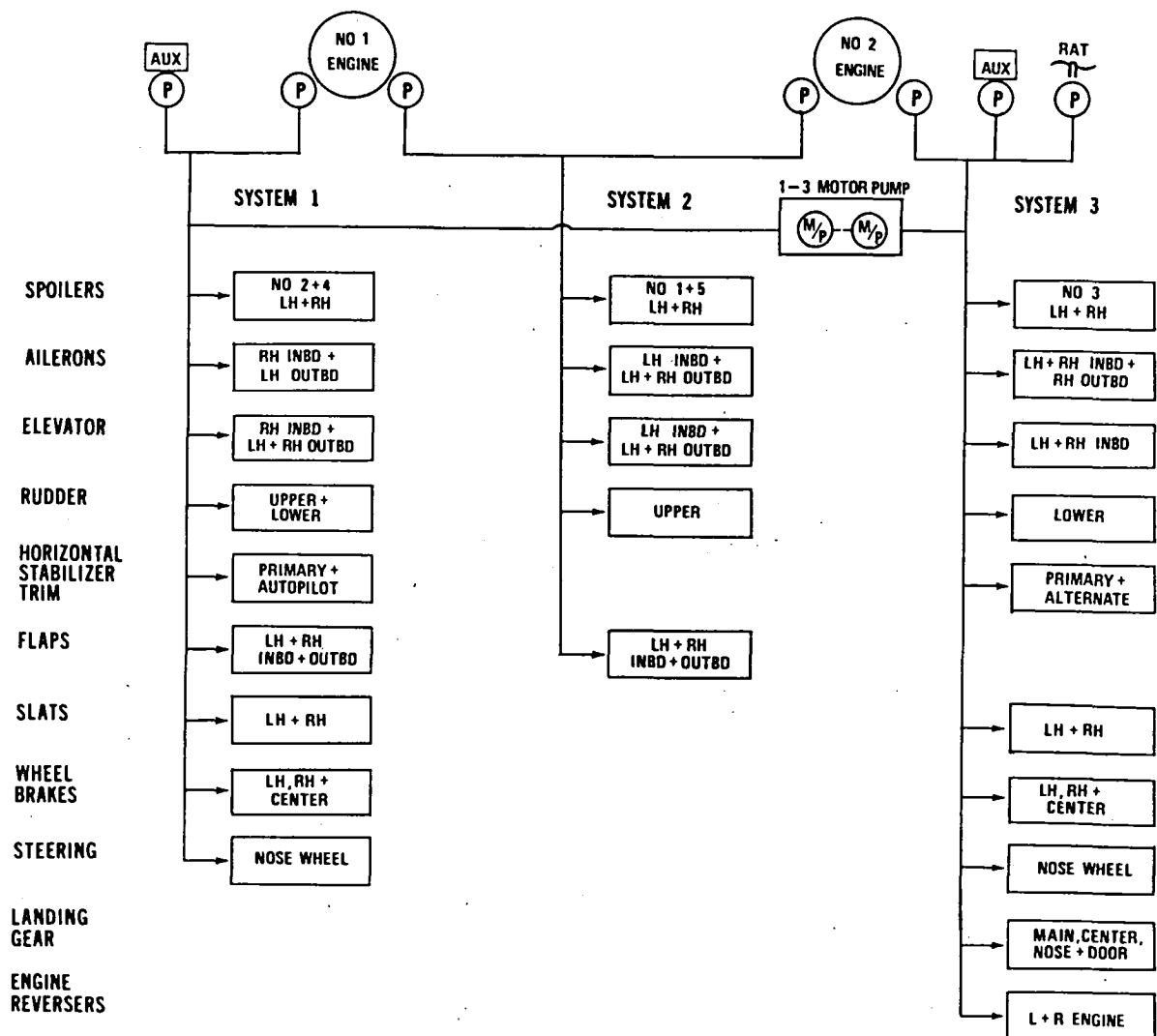


FIGURE C2. HYDRAULIC SYSTEM BLOCK DIAGRAM

APPENDIX D
TASK AND INFORMATION REQUIREMENT ANALYSES FOR
THE FUEL AND THE HYDRAULIC SYSTEMS

For each of the systems described in Appendix C, analyses were performed of the normal procedures and one contingency. These analyses included the following:

1. TASK FLOW ANALYSIS. This included all decisions and actions required by the crew according to a sequential, iterative model. This model is iterated from mission initiation until it is either completed or aborted.
2. INFORMATION REQUIREMENTS ANALYSIS. For each task listed in the task flow analysis the information required to complete a task is identified for each phase of flight.
3. OPERATIONAL SEQUENCE ANALYSIS. This is a sequence of tasks (both the crew and automated tasks) required to collect the information and perform the decision and action tasks. A subsequent analysis was performed for only the crew's tasks.
4. INFORMATION CLASSIFICATION. After each information requirement is identified it is classified according to the type (e.g., identifier, descriptor, status, or instruction), the type of scale used for presenting the information, and the source of the information.

The task and information requirement analyses are presented for the normal procedures of both systems in Figure D1 and D3. Analyses are also presented for an imbalance contingency of the fuel system in Figure D2 and a dual hydraulic system in Figure D4. The operational sequence analysis and the information classification are presented in Figures D5 to D8.

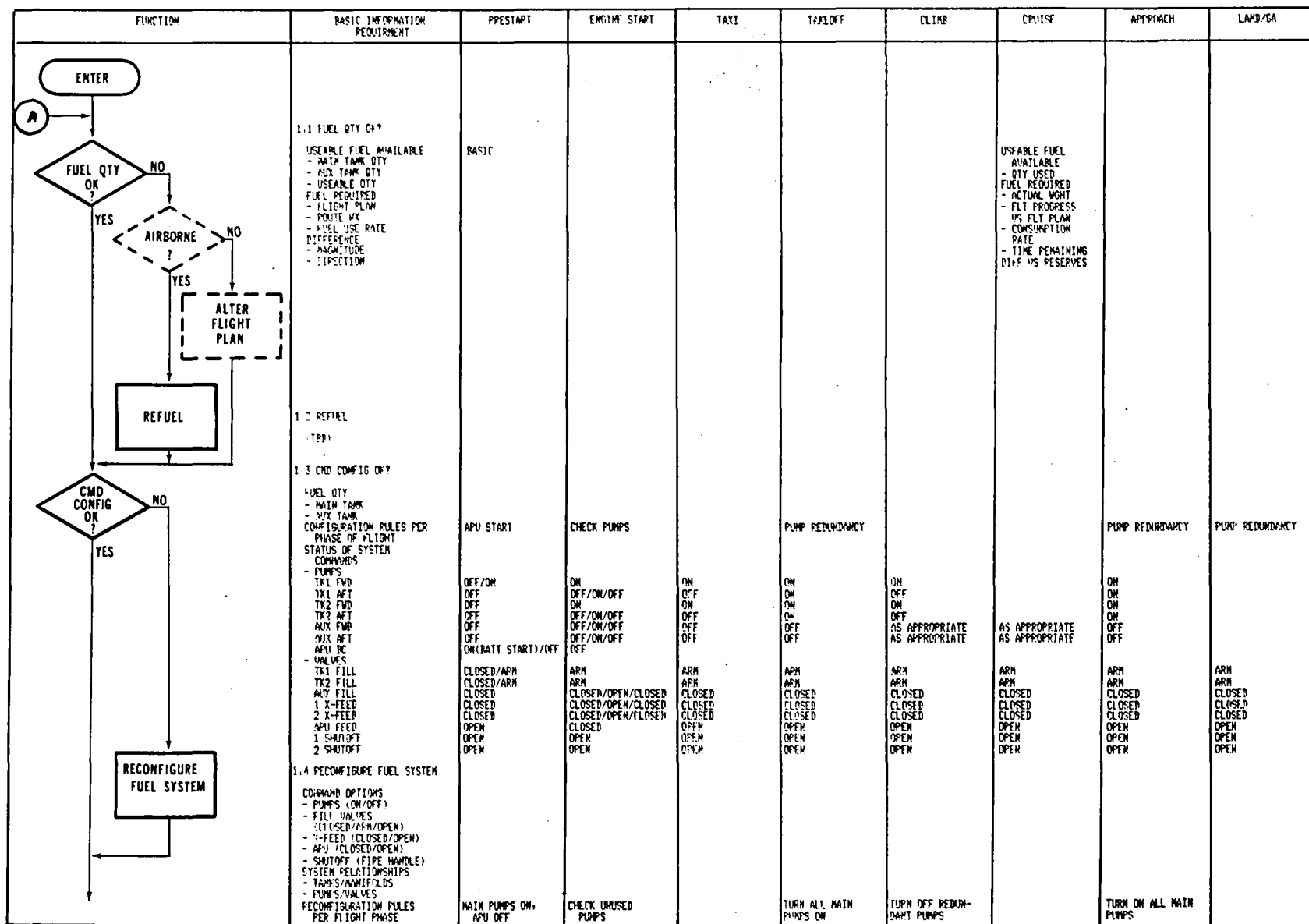


FIGURE D1. INFORMATION REQUIREMENT ANALYSIS FOR THE FUEL SYSTEM'S NORMAL PROCEDURES

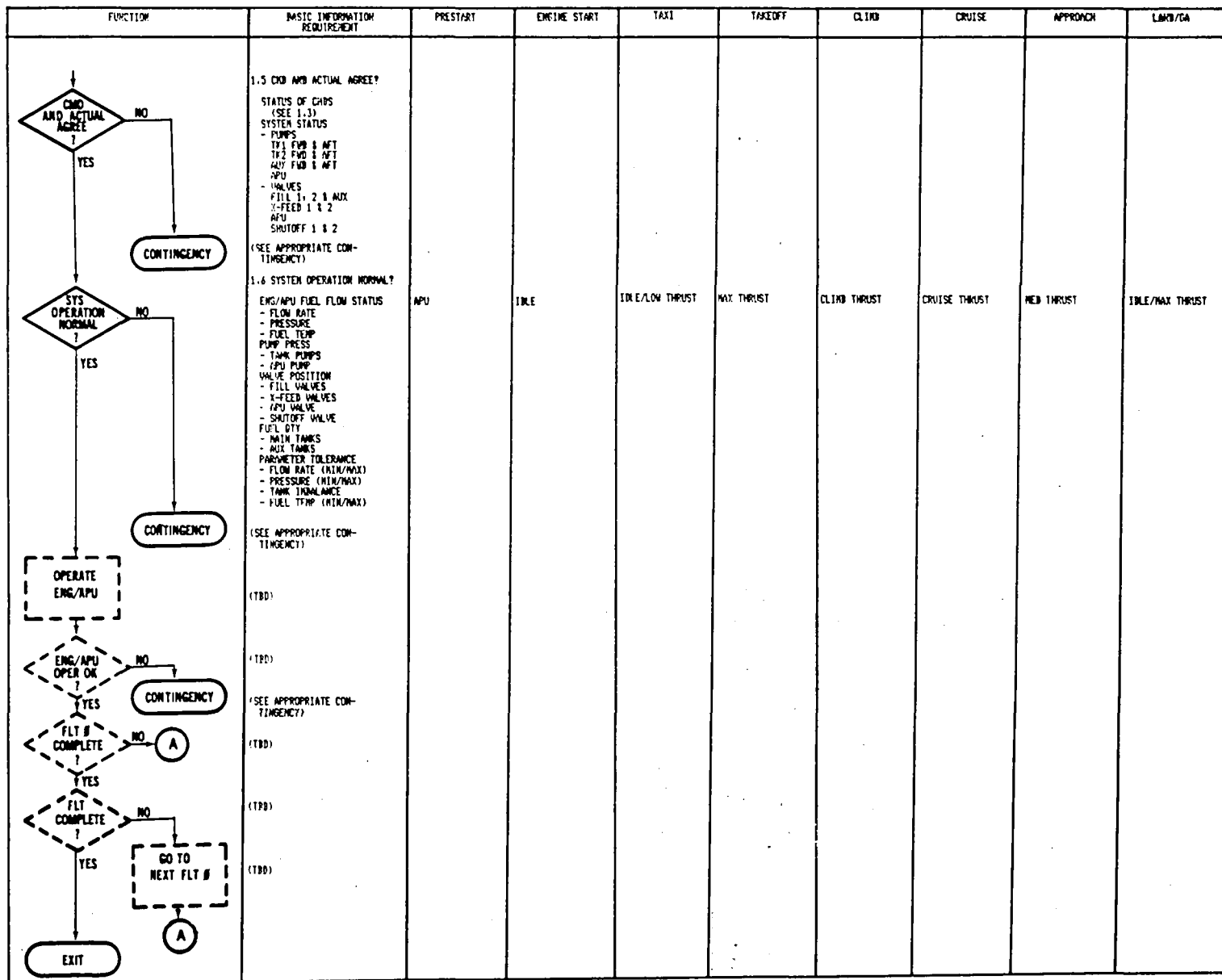


FIGURE D1. INFORMATION REQUIREMENT ANALYSIS FOR THE FUEL SYSTEM'S NORMAL PROCEDURES (Continued)

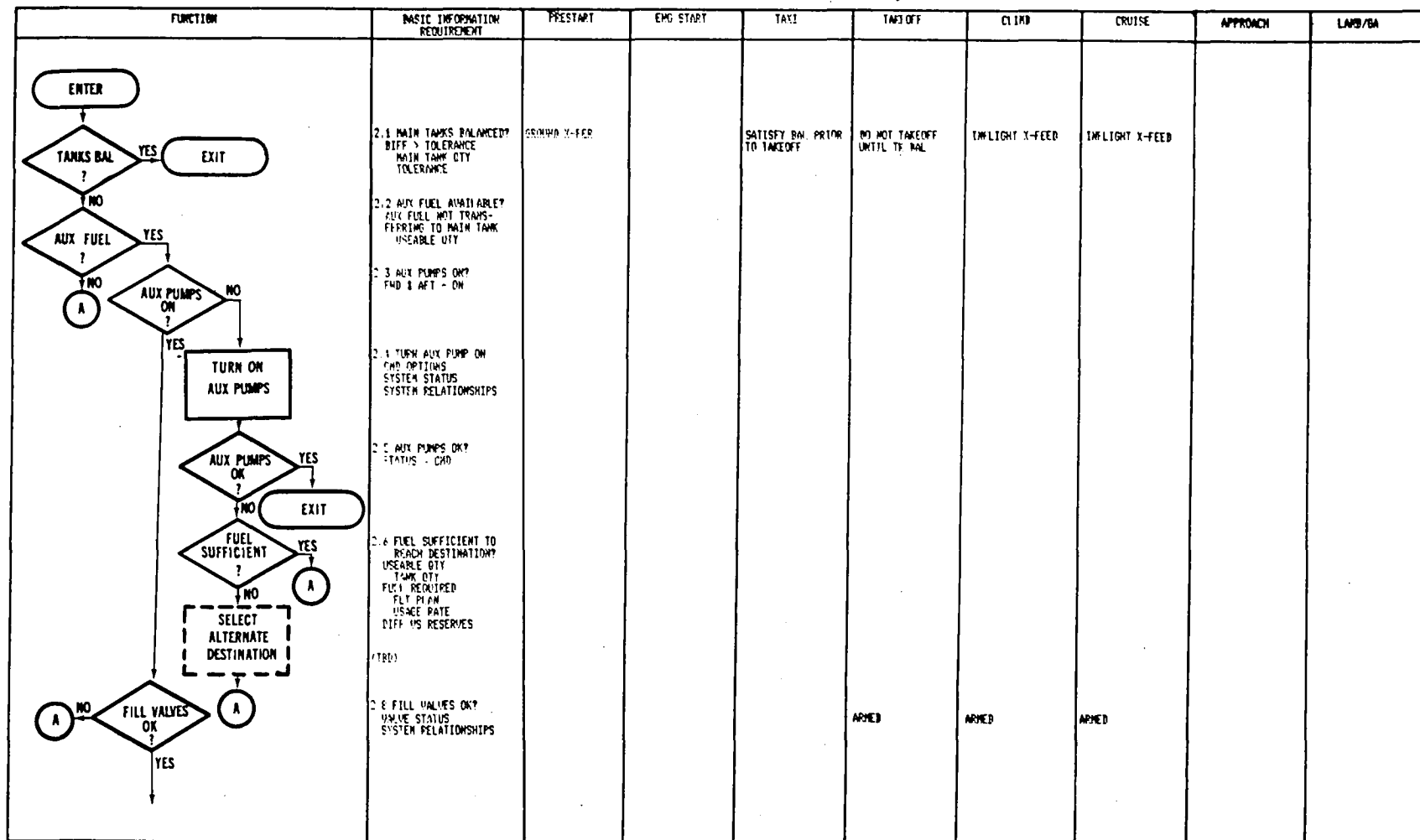


FIGURE D2. INFORMATION REQUIREMENT ANALYSIS FOR THE FUEL SYSTEM'S TANK IMBALANCE PROCEDURES

FUNCTION	BASIC INFORMATION	PRESTART	ENG START	TAXI	TAKEOFF	CLIMB	CRUISE	APPROACH	LAND/BA
<pre> graph TD Start(()) --> ManualOverride[MANUAL OVERRIDE] ManualOverride --> FillValve{FILL VALVE OK?} FillValve -- NO --> ManualOverride FillValve -- YES --> TanksBal1{TANKS BAL?} TanksBal1 -- NO --> FillValve TanksBal1 -- YES --> CloseFillValve[CLOSE FILL VALVE] CloseFillValve --> Exit1([EXIT]) Exit1 -- A --> XFeed[X-FEED] XFeed --> TanksBal2{TANKS BAL?} TanksBal2 -- NO --> XFeed TanksBal2 -- YES --> StopXFeed[STOP X-FEED] StopXFeed --> Exit2([EXIT]) </pre>	<p>2.9 MANUAL OVERRIDE SWITCH CMD OPTIONS SYSTEM RELATIONSHIPS</p> <p>2.10 FILL VALVE OK? STATUS = CMD</p> <p>2.11 TANKS BALANCED? DIFFERENCE > TOLERANCE</p> <p>2.12 CLOSE FILL VALVE CMD OPTIONS SYSTEM RELATIONSHIPS</p> <p>2.13 X-FEED CMD OPTION PUMPS-MAIN & AUX TANKS X-FEED VALVES DIFFERENCE DIRECTION SYSTEM RELATIONSHIPS</p> <p>2.14 TANKS BALANCED? DIFFERENCE > TOLERANCE</p> <p>2.15 STOP X-FEED CMD OPTIONS PUMPS-MAIN & AUX TANKS X-FEED VALVES</p>	GROUND FUEL X-FER			OPEN	OPEN	OPEN		
					CLOSE	CLOSE	CLOSE		
						LO TK-OFF+ BOTH ON IN AUX OR HI TK IF MAIN TK-NOTH+IF AUX TK-LO SIDE			
						LO TK-ON+1 OFF IN AUX OR HI TK X-FEED-CLOSE			

FIGURE D2. INFORMATION REQUIREMENT ANALYSIS FOR THE FUEL SYSTEM'S TANK IMBALANCE PROCEDURES (Continued)

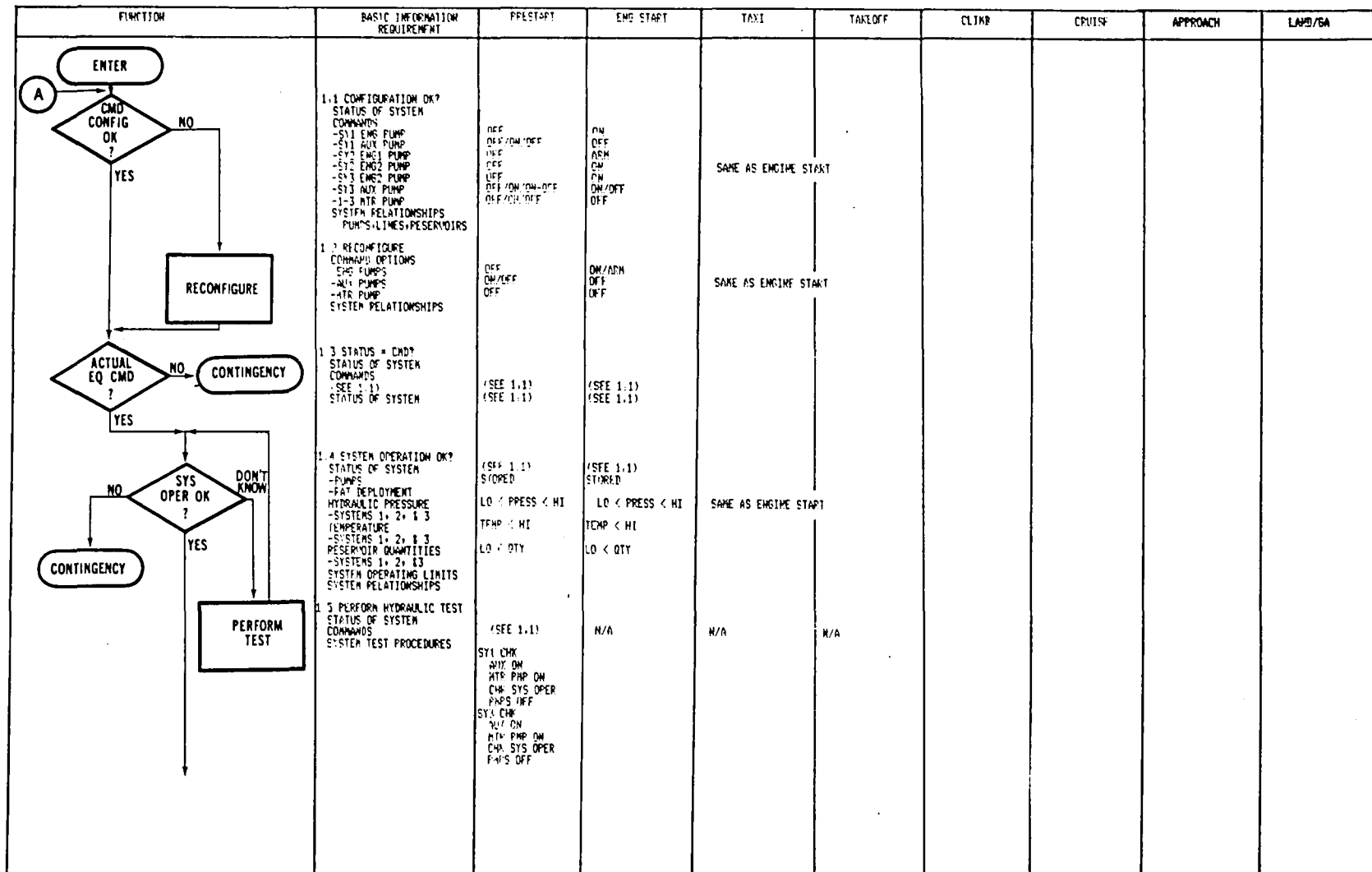


FIGURE D3. INFORMATION REQUIREMENT ANALYSIS FOR THE HYDRAULIC SYSTEM'S NORMAL PROCEDURES

FUNCTION	BASIC INFORMATION	PRESTART	ENG. START	TAXI	TAKEOFF	CLIMB	CRUISE	APPROACH	LAND/BA
<pre> graph TD Start([]) --> Operate[OPERATE HYDRAULIC CONTROLS] Operate --> D1{FLT # COMPLETE?} D1 -- NO --> A1((A)) D1 -- YES --> D2{FLT COMPLETE?} D2 -- NO --> A2((A)) D2 -- YES --> GoNext[GO TO NEXT FLT #] GoNext --> A3((A)) A1 --> Exit([EXIT]) A2 --> Exit A3 --> Exit </pre>	(TRD)								
	(TRD)								
	(TRD)								
	(TRD)								

FIGURE D3. INFORMATION REQUIREMENT ANALYSIS FOR THE HYDRAULIC SYSTEM'S NORMAL PROCEDURES (Continued)

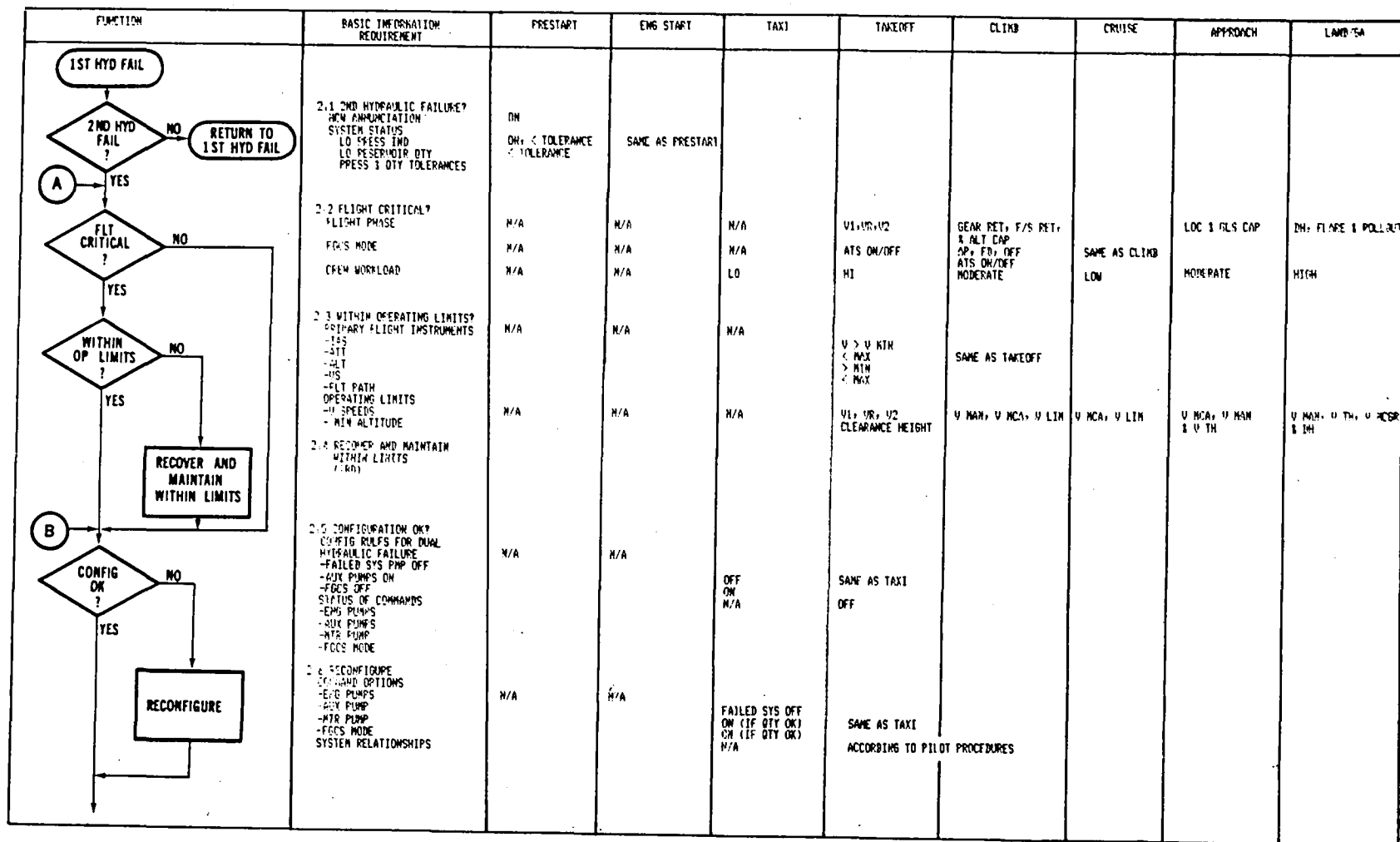


FIGURE D4. INFORMATION REQUIREMENT ANALYSIS FOR THE HYDRAULIC SYSTEM'S DUAL FAILURE PROCEDURES

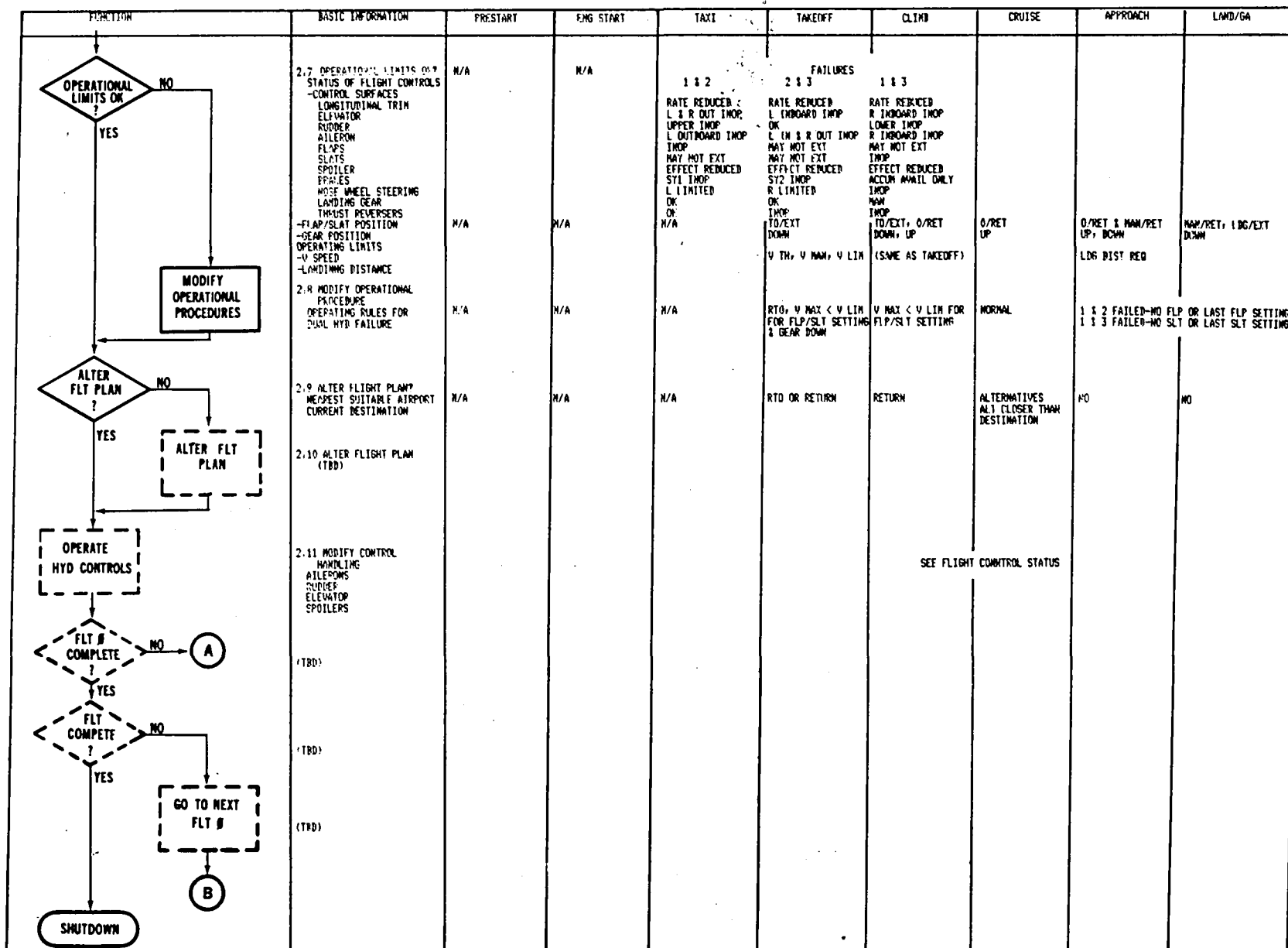


FIGURE D4. INFORMATION REQUIREMENT ANALYSIS FOR THE HYDRAULIC SYSTEM'S DUAL FAILURE PROCEDURES (Continued)

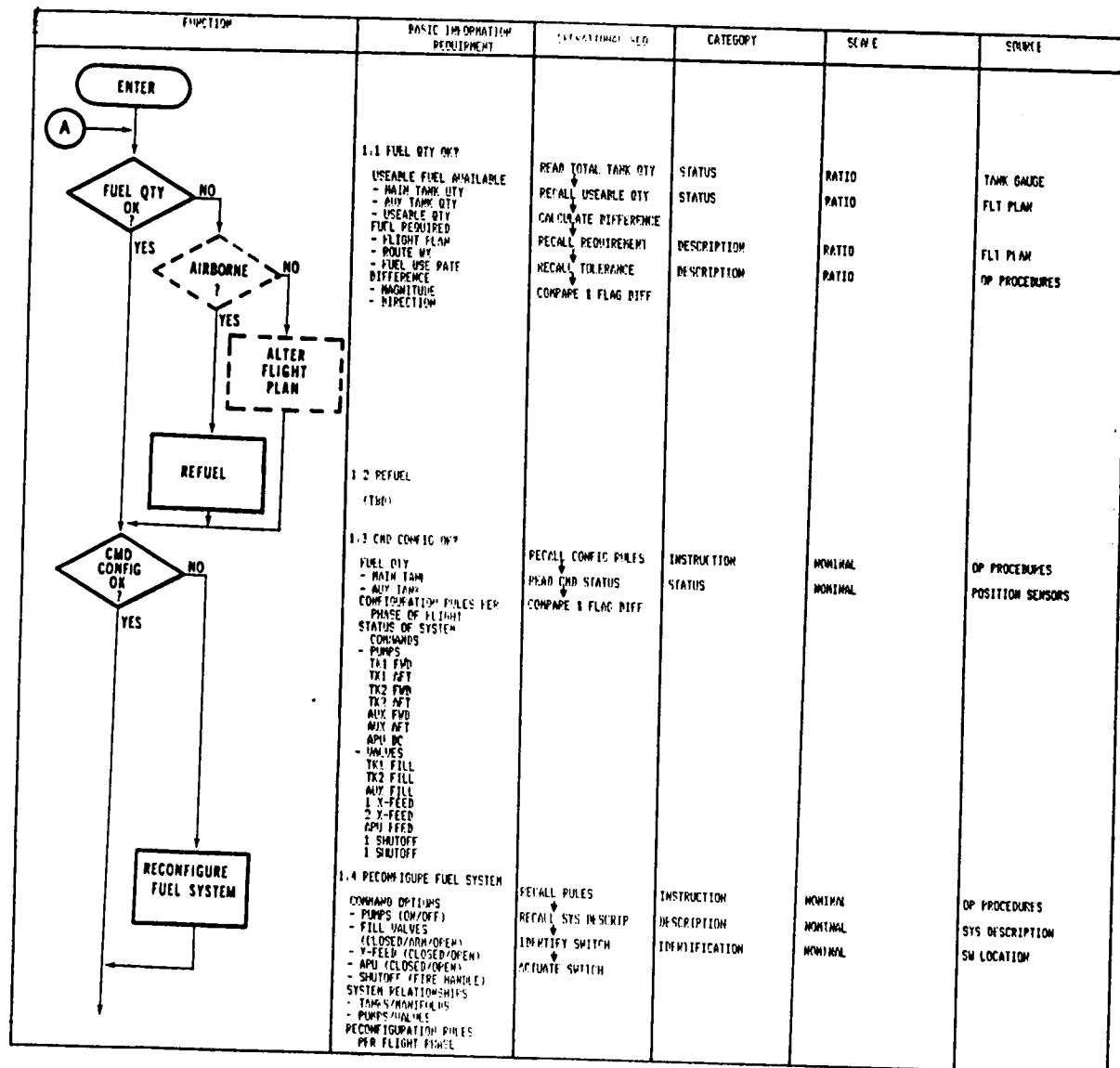


FIGURE D5. OPERATIONAL SEQUENCE ANALYSIS FOR THE FUEL SYSTEM'S NORMAL PROCEDURES

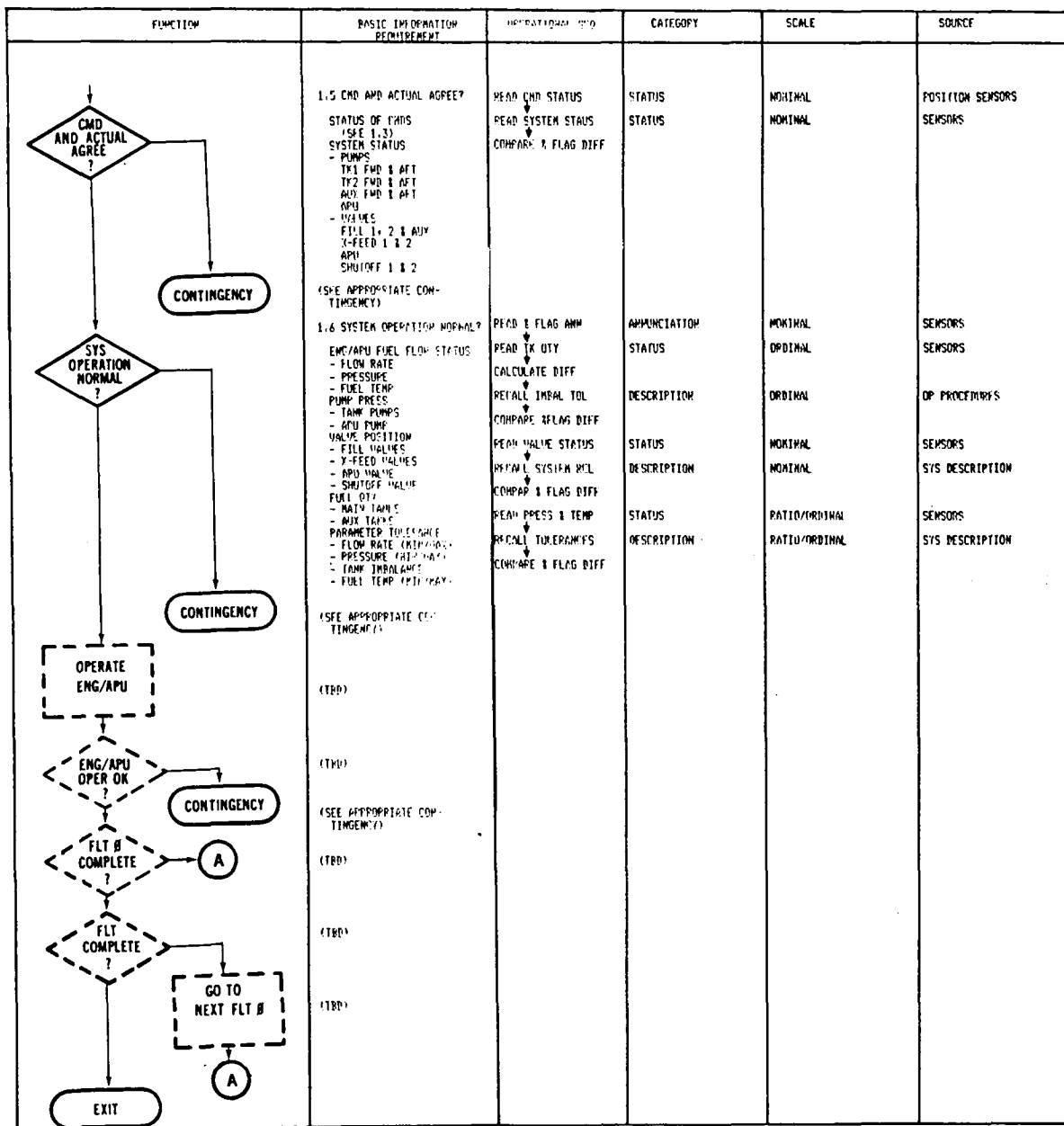


FIGURE D5. OPERATIONAL SEQUENCE ANALYSIS FOR THE FUEL SYSTEM'S NORMAL PROCEDURES
(Continued)

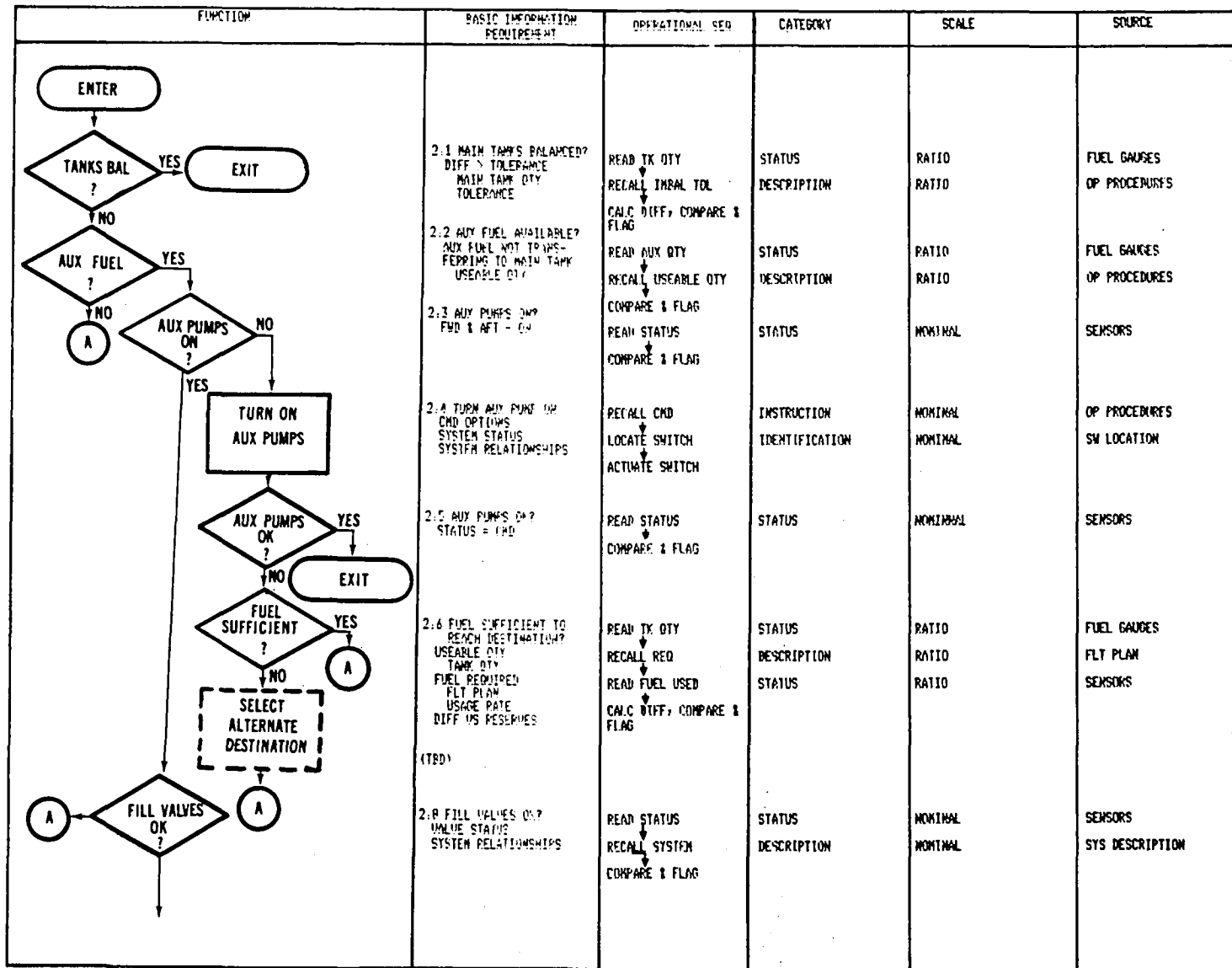


FIGURE D6. OPERATIONAL SEQUENCE ANALYSIS FOR THE FUEL SYSTEM'S TANK IMBALANCE PROCEDURES

FUNCTION	BASIC INFORMATION	OPERATIONAL SEQ	CATEGORY	SCALE	SOURCE
<pre> graph TD Start(()) --> ManualOverride[MANUAL OVERRIDE] ManualOverride --> FillValveOK{FILL VALVE OK A} FillValveOK --> TanksBal1{TANKS BAL ?} TanksBal1 -- YES --> CloseFillValve[CLOSE FILL VALVE] CloseFillValve --> Exit1([EXIT]) TanksBal1 -- NO --> FillValveOK </pre>	<p>2.9 MANUAL OVERRIDE SWITCH CMD OPTIONS SYSTEM RELATIONSHIPS</p> <p>2.10 FILL VALVE OK? STATUS = CMD</p> <p>2.11 TANKS BALANCED? DIFFERENCE > TOLERANCE</p> <p>2.12 CLOSE FILL VALVE CMD OPTIONS SYSTEM RELATIONSHIPS</p>	<p>RECALL CMD OPTIONS ↓ RECALL SYSTEM ↓ LOCATE SWITCH ↓ ACTUATE SWITCH ↓ READ STATUS ↓ COMPARE 1 FLAG</p> <p>READ TK QTY ↓ CALC DIFF ↓ RECALL TOLERANCE ↓ COMPARE</p> <p>RECALL CMDS ↓ IDENTIFY SWITCH ↓ ACTUATE SWITCH ↓ READ STATUS</p>	<p>INSTRUCTION</p> <p>DESCRIPTION</p> <p>IDENTIFICATION</p> <p>STATUS</p> <p>STATUS</p> <p>DESCRIPTION</p> <p>INSTRUCTION</p> <p>IDENTIFICATION</p> <p>STATUS</p>	<p>NOMINAL</p> <p>NOMINAL</p> <p>NOMINAL</p> <p>NOMINAL</p> <p>RATIO</p> <p>RATIO</p> <p>NOMINAL</p> <p>NOMINAL</p> <p>NOMINAL</p>	<p>OP PROCEDURES</p> <p>SYS DESCRIPTION</p> <p>SW LOCATION</p> <p>SENSORS</p> <p>FUEL GAUGES</p> <p>OP PROCEDURES</p> <p>OP PROCEDURES</p> <p>SW LOCATION</p> <p>SENSORS</p>
<pre> graph TD Start(()) --> XFeed[X-FEED] XFeed --> TanksBal2{TANKS BAL ?} TanksBal2 -- YES --> StopXFeed[STOP X-FEED] StopXFeed --> Exit2([EXIT]) TanksBal2 -- NO --> XFeed </pre>	<p>2.13 X-FEED CMD OPTION PUMPS-MAIN & AUX TANKS X-FEED VALVES DIFFERENCE DIRECTION SYSTEM RELATIONSHIPS</p> <p>2.14 TANKS BALANCED? DIFFERENCE > TOLERANCE</p> <p>2.15 STOP X-FEED CMD OPTIONS PUMPS-MAIN & AUX TANKS X-FEED VALVES</p>	<p>RECALL CONFIG RULES ↓ DETERMINE FEED TK ↓ DETERMINE DIRECTION ↓ IDENTIFY SWITCHES ↓ ACTUATE SWITCHES ↓ READ STATUS</p> <p>READ TK QTY ↓ CALC DIFF ↓ RECALL TOLERANCE ↓ COMPARE</p> <p>RECALL CONFIG RULES ↓ IDENTIFY SWITCHES ↓ ACTUATE SWITCHES ↓ READ STATUS</p>	<p>INSTRUCTION</p> <p>STATUS</p> <p>DESCRIPTION</p> <p>IDENTIFICATION</p> <p>STATUS</p> <p>STATUS</p> <p>DESCRIPTION</p> <p>INSTRUCTION</p> <p>IDENTIFICATION</p> <p>STATUS</p>	<p>NOMINAL</p> <p>RATIO</p> <p>NOMINAL</p> <p>NOMINAL</p> <p>NOMINAL</p> <p>RATIO</p> <p>RATIO</p> <p>NOMINAL</p> <p>NOMINAL</p> <p>NOMINAL</p>	<p>OP PROCEDURES</p> <p>FUEL GAUGES</p> <p>SYS DESCRIPTION</p> <p>SW LOCATION</p> <p>SENSORS</p> <p>FUEL GAUGES</p> <p>OP PROCEDURES</p> <p>OP PROCEDURES</p> <p>SW LOCATION</p> <p>SENSORS</p>

FIGURE D6. OPERATIONAL SEQUENCE ANALYSIS FOR THE FUEL SYSTEM'S TANK IMBALANCE PROCEDURES (Continued)

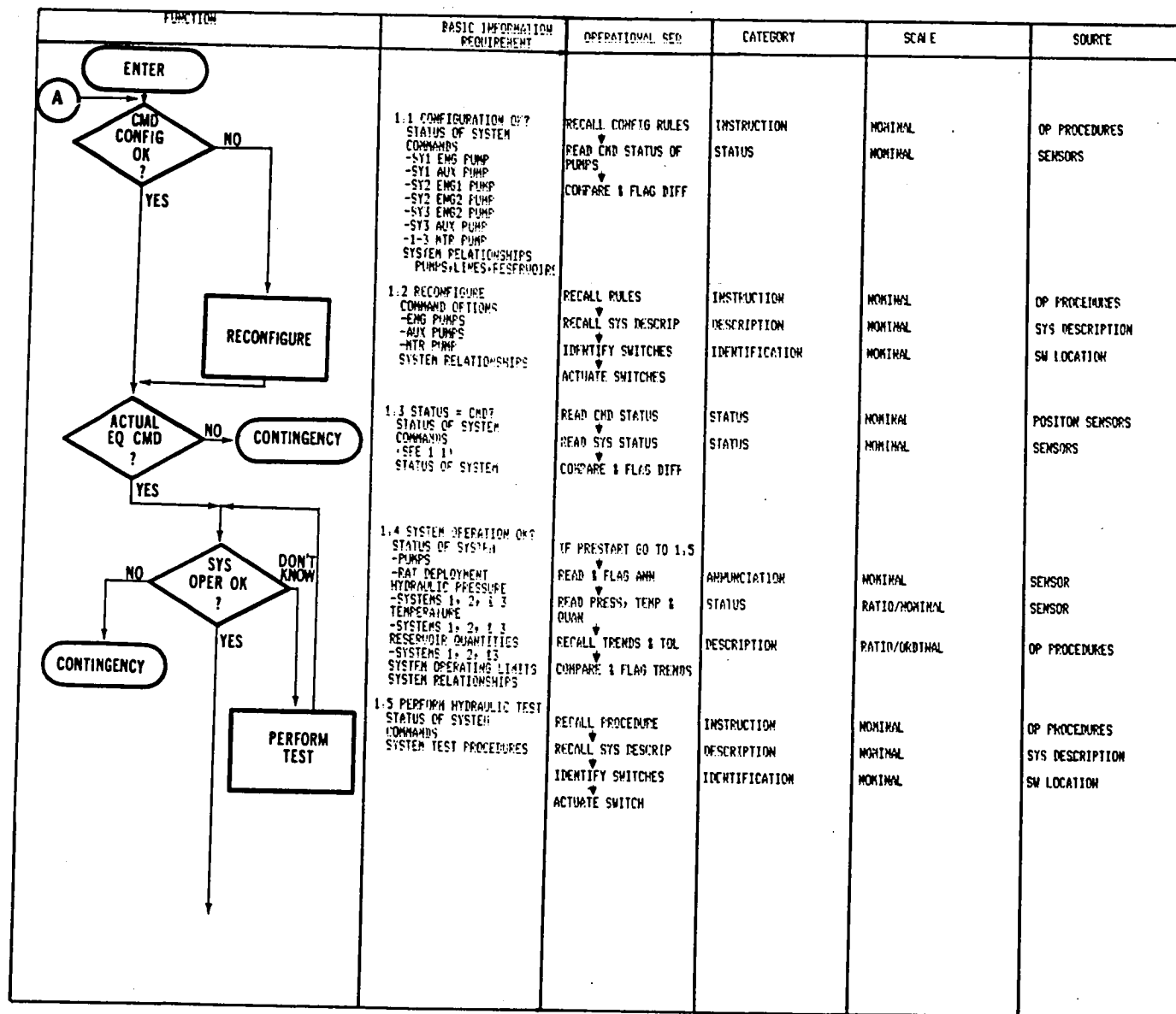


FIGURE D7. OPERATIONAL SEQUENCE ANALYSIS FOR THE HYDRAULIC SYSTEM'S NORMAL PROCEDURES

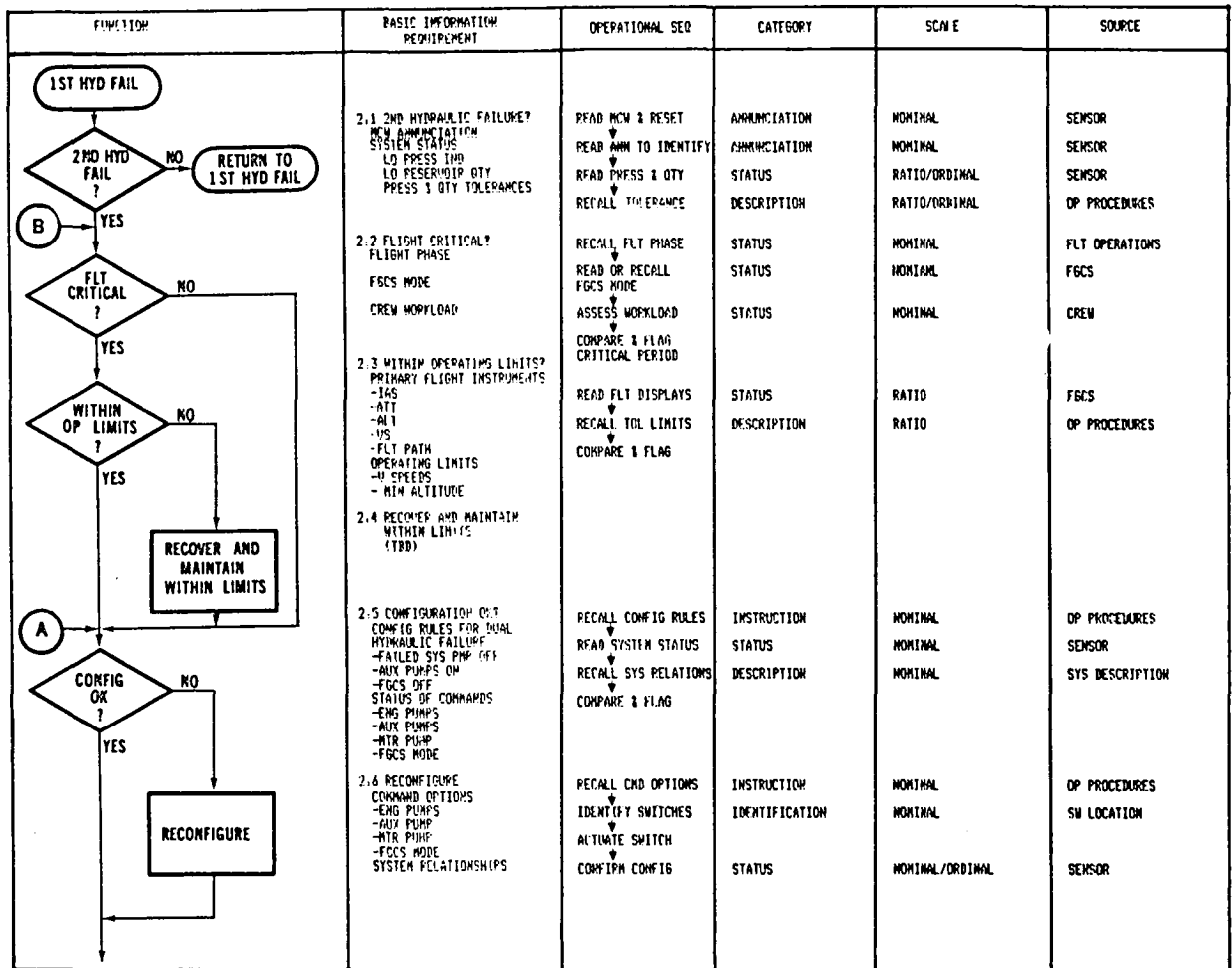


FIGURE D8. OPERATIONAL SEQUENCE ANALYSIS FOR THE HYDRAULIC SYSTEM'S DUAL FAILURE PROCEDURES

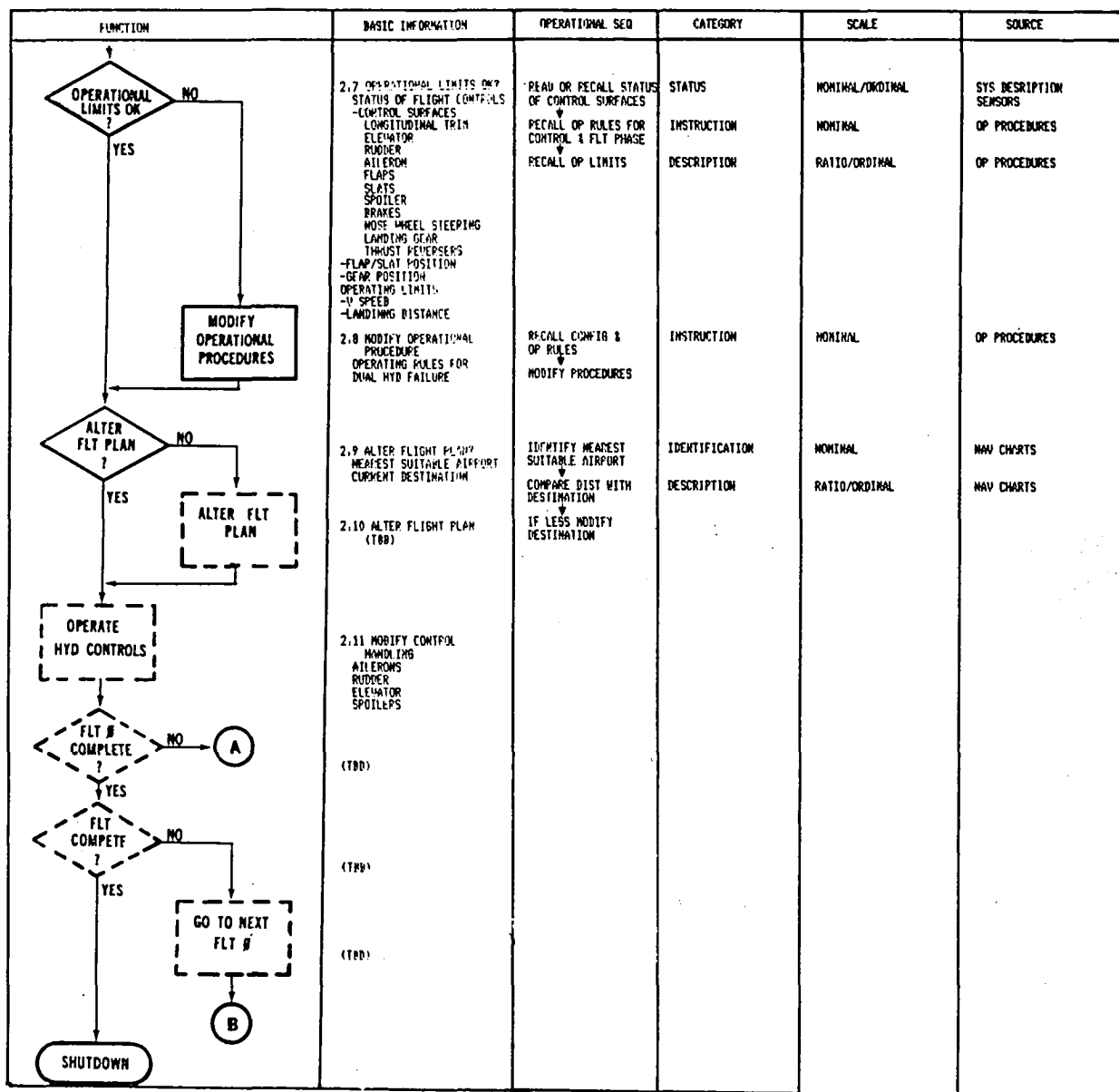


FIGURE D8. OPERATIONAL SEQUENCE ANALYSIS FOR THE HYDRAULIC SYSTEM'S DUAL FAILURE PROCEDURES (Continued)

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18. Abstract <p>The System Status Display study is part of the Advanced Transport Operating Systems program and is directed toward the development of advanced display information for flight deck operations of future commercial aircraft. The System Status Display is an electronic display system which provides the crew with enhanced capabilities for monitoring and managing aircraft systems. The objective of the study is to establish guidelines for the design of electronic system displays. The technical approach to this problem involves the application of a system engineering approach to the design of candidate displays and the evaluation of alternative concepts by part-task simulation. This report covers the system engineering portion of the study and selection of candidate displays.</p>					
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